Land use strategies of the ancient Maya in seasonally dry tropical forest ecosystems of the Yucatan Peninsula

A thesis presented in accordance with the requirements for the degree of Doctor of Philosophy

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March 2020

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Abstract

Throughout the history of human-environmental interactions in Central America, the ancient Maya are one of the most contested regarding the extent to which their land-use strategies degraded their environment. For over 3500 years, the ancient Maya manipulated plant communities by promoting economically important species and removing those that had little use. These strategies potentially impacted the modern forests of Central America, by creating a legacy of economically important species in the modern assemblages. Along with the promotion of useful species, the ancient Maya also consistently introduced fire into ecosystems that would have limited natural exposure and to some extent removed forest vegetation for settlement structures. It is this extent of forest removal that remains one of the most contentious aspects of our understanding of ancient Maya land-use strategies. Palaeoecological records (fossil pollen evidence) throughout Central America shows a strong signal for extensive forest cover removal (declining arboreal pollen) and maize agriculture, leading many to suggest these processes were closely related to population pressures and food demand. These signals for supposed deforestation have been added to a pre-existing link between climate drying and societal collapse (*ca* 750-1100 CE), leading many to suggest that extensive environmental degradation was one of the major drivers of the collapse of the Classic Maya Civilisation. Whilst the evidence for intensive drought is founded in robust palaeoclimate records throughout Central America and the evidence for the societal decline is well documented across many settlements throughout the region, the evidence for deforestation is not yet as well established. To date, the majority of records that interpret these phases of deforestation are located in assumed high population density centres. These sites are then often extrapolated to the entirety of the ancient Maya society, resulting in little attention being paid to how different types of settlements may have interacted with the forest environment.

Here we show two new palaeoecological investigations from lower-density settlements, with one being the first palaeoecological representation of ancient Maya land-use from an island site. Pollen and charcoal records were used to determine changes in vegetation and the fire regime associated with ancient Maya land-use from the seasonally dry tropical forested ecosystems of the Yucatan Peninsula. Comparisons between an inland (Laguna Esmeralda) and island (Ambergris Caye) reveal similarities regarding the extent in which the forest was impacted by periods of cultivation, but also differences regarding how activities changed in response to periods of drought. This research presents two new

chronological baselines for *Zea mays* cultivation on the mainland (5.5 kyr cal. BP) and the island (4.8 kyr cal. BP) showing these regions were actively managed long before previously suggested. In addition to the long-term records of ancient Maya land-use, a series of surface samples from Laguna Esmeralda and the adjacent Lake Chichancanab to uncover how the modern forest is represented in these two different sized lakes and aid in the interpretation of the palaeoecological records.

Using these interpretations of ancient Maya land-use from lower-density settlements, this research shows that the aforementioned hypothesis of extreme environmental degradation likely only represents a perspective from higher-density settlements. The strong associations between periods of land-use and drought conditions are prominent during the Terminal Classic Period (750/1000 CE), where clear reductions in arboreal pollen are interpreted to reflect localised forest clearances and intensification of cultivation around a valuable water resource. Further adaptions to drought periods are also evident from Ambergris Caye, with combined previous archaeological and current palaeoecological evidence showing the use of mixed resources during the Preclassic Abandonment Period (~250 CE). Ambergris Caye acted as a climate refuge for the ancient Maya, providing a new lens of analysis for understanding ancient Maya adaptions to instability and showing the importance of island sites in the wider perspective of the ancient Maya civilisation.

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Terminology used in Thesis

Terminology	**Definition**
Forest cover	The percentage (%) of forest vegetation species recorded in the palaeoecological record
Land-use	Methods of human activity on a landscape that produced subsistence or other economic benefits
Environmental degradation	A process in which the environment is continuously depleted by human activities
Chronological baseline	The earliest empirical evidence for a form of activity
kyr BP	Thousand years before present
kyr cal. BP	Calibrated thousand years before present
BCE/CE	Before Common Era/Common Era
Ancient Maya	A prehispanic civilization that inhabited Central America between approx. 2500 BCE to 1500 CE
The Lowlands	The low topographic regions of Central America, primarily Belize, the Yucatan Peninsula and parts of Guatemala
The Highlands	The mountainous regions of Central America, mainly Western Mexico/Guatemala, Honduras and parts of El Salvador
The Yucatan Peninsula	The region of Central America that consists of the modern states of Yucatan, Campeche, Quintana Roo and parts of Belize, Mexico and Guatemala
Pre-Hispanic	The peoples of Central America who lived on the landscape before the first contact with the Spanish in *ca* 1509 CE

Cultivation	Small scale management of crops likely to support individual/small communal needs
Agriculture	Larger scale management of crops to support wider systems of food
Sinkhole	A dissolution feature of a karst landscape that contains freshwater
Milpa	A traditional form of agriculture that uses periods of fire activity to clear the landscape in routine cycles to maximise agriculture production

Acknowledgments

This thesis is dedicated to the person who walked me to school every day, made my packed lunches and made sure I did my homework well before dinner time. I know all the candles and prayers you said for me paid off. To my granny Mona Meade, without you through all these times, none of this would have been possible (RIP 16/03/2020).

Secondly to Mairead Handley, whose calls every night, endless encouragement and faith in me since we met has been the motivating force behind everything I do. I can't wait to start the next chapter of our life together. To Dermot Handley, thank you for always taking an interest in things I was doing. It meant so much to me when how always asked about to project and not to mention the lifts to the airport every Monday Morning. Thank you to Lilly Handley who was always great for a chat and an apple pie. To my mother, Angela, thank you for always picking me up from the airport and giving me a place to stay. To my Dad, thanks for always helping out when I needed it and for dinner every Thursday. To my brother and sister, Carl and Nikki, thanks so much for your encouragement in the final stages of writing this and for pushing me that extra mile when I needed it.

This thesis and whole PhD project would not have been possible without the institutional support provided by the geography department of Northumbria University. To my primary supervisor. Dr. Bronwen Whitney, thank you for being so much more than a supervisor throughout this and always pushed me to be my best. You were a true mentor throughout this whole project and I'm so glad you adopted me into the Tropical family. Thank you for all the advice, I'll carry it with me forever. Thank you to my second supervisor, Dr. Nicholas Loughlin, who came from what seemed like nowhere, but made an unbelievable contribution to this project. I valued every conversation we had, only about pollen of course and I promise one day I'll return and beat you in pool, once and for all. Thank you to my third supervisor, Dr. Mike Jeffries, thank you for all the feedback and chats we had, I promise the next thesis will include more aliens. To contributors Dr. Julie Hoggarth and Prof. Sarah Metcalfe, thank you for always being available to answer any question I had ranging from palaeoenvironmental to archaeological. Thank you to all the lecturers in the Geography department who made such a huge impact on my time there, I promise to continue to do what I can on the bad days and my best on the good days.

Some important people in this geography department deserve special thanks. To Cal, I'm sure you were thrilled sitting beside me for three years, but I do consider you a lifelong

friend!! I wish you, Sarah and of course Rolo all the best in the future!! To Lucie, our adopted sibling from life science, thank you for helping organise Thesis Friday, which did eventually become Thesis every day. Thank you to Seb for always housing me when I came to visit and being a great pool partner. Thanks to Jim and all the ice people for becoming part of the PGR community and being fantastic lunch company. To Beckie Stewart, like Nick, I promise to come back and beat you in pool as well. To everybody else in A203 and A221 who I don't have room to thank individually, thank you all for making Newcastle my home.

Authors declaration

I declare that the work submitted in this thesis has not been submitted for any other award and it is my own work. I also confirm that this work acknowledges opinions, ideas and contributions from others. Any ethical clearances for this research have been approved through the University Ethics Committee (approved on 22/02/2017).

I declare that the word count of this thesis is 54894 words including referencing and captions.

Name: Adam Bermingham

Date: 25/03/2020

Chapter 1 Introduction

1:1 Overview

This chapter outlines the background context for this research topic, discusses human environmental changes and the thinking behind these relations, whilst also introducing the primary ecological context of this research, seasonally dry tropical forests. The approach and research aims/questions are then outlined, justifying the sampling strategy employed.

1:2 Human impacts in the Anthropocene

Human impacts on the earth's surface and atmosphere are, geologically speaking, a recent phenomenon. Despite being "recent" features on the landscape, humans have profoundly impacted the earth's global system, justifying the declaration of a new geological epoch known as the Anthropocene (Crutzen, 2002, 2006). The appreciation for this new age of anthropogenic activities is primarily driven by the increased release of CO_2 into the atmosphere, which influences the natural fluctuations of this gas in the atmosphere and increasing surface temperatures, resulting in the delaying of the next glaciation event (Stocker *et al.*, 2013; Wolff, 2014; Shukla *et al.*, 2019). Increasing CO_2 concentrations in the atmosphere is not the only impact humans have had on earth's systems, with ocean acidification (Stocker *et al.*, 2013) and ecological degradation driving the extinction of species at 100-1000 times greater than background rates (Barnosky *et al.*, 2011). Dating the Anthropocene as a geological epoch requires a distinct, global, stratigraphic marker to distinguish human activities from background variations in long-term change (Lewis and Maslin, 2015; Zalasiewicz *et al.*, 2017). These markers have large temporal ranges of when humans began to markedly influence their environment, ranging from the megafaunal extinctions of the Late Pleistocene (Braje and Erlandson, 2013; Barnosky *et al.*, 2016; Malhi *et al.*, 2016) to the fallout of nuclear warfare dating the early 1950s (Zalasiewicz *et al.*, 2015; Carrington, 2016; Brunnengräber and Görg, 2017). Within these ranges, the onset of agricultural represents an important point to distinguish when land-use first becomes preserved in the geological record, although the spatial variability of its onset limits its reliability of being a global geological marker for the Anthropocene. Potential cultivation of a wild crop is shown in the Fertile Crescent during the Pleistocene-Holocene transition between 11.7-10.3 kyr cal. BP, a time when precipitation was higher in the region (Bar-Yosef, 2014, 2017). Cultivation then appears in China (Bestel *et al.*, 2014),

South America (Medina, Pastor and Recalde, 2016), Central America (Piperno and Flannery, 2001), Africa (Wengrow *et al.*, 2014) and Mediterranean Europe (Vigne, 2015, 2016) between 11 and 8 kyr cal. BP, later established in South-East Asia by 4.5 kyr cal. BP (Bellwood, 2005; Higham, 2015)**.** These records present important opportunities to understand when humans began to modify the landscape to such an extent to genetically change wild species to their modern-day domesticated versions (Matsuoka *et al.*, 2002; Pohl *et al.*, 2007; Vallebueno-Estrada *et al.*, 2016), with palaeoecological evidence used to improve the understanding the environmental impact associated with these early cultivation activities.

Alongside the development of agriculture, human control of fire marks a distinctive process in human history that had profound impacts on our ability to modify the landscape. The archaeological record represents the best evidence available to understand when hominid species began to control this natural resource. Fire pits, with burnt tools, have been found in Kenya (Africa) dated between 1-0.5 million years ago (Bellomo and Kean, 1997; Rowlett, 2000), with its expansion into Europe and Asia occurring approximately 400,000 years ago (Black, 1934; Oakley, 1956; Rolland, 2000; Gowlett, 2006). Palaeoecological records, studying the deposition of micro/macro charcoal deposits in sediment cores, have improved the understanding of fire use in the Americas, with records showing its use in Alaska between 14 kyr BP (kyr = 1000 years) (Higuera *et al.*, 2008) and Central/South America between 13.5-11.5 kyr BP (Moreno and León, 2003; Piperno and Jones, 2003). Whilst anthropogenic use of fire cannot be a distinct marker for the beginning of the geological Anthropocene, it represents one of the most crucial developments in our evolution and is of little surprise of its importance to modern society. However, the modern intensification of fire to maximise industrial (coal burning) and agricultural (conversion of landscapes into pastures) resources, combined with climate change, has accelerated our growing influence of modifying the Earth's surface. Ecosystem change, loss of biodiversity and the extinction of animals particularly are all bi-products of this intensification, with global recognition for the urgency to deal with these issues particularly evident from the Amazonian forest fires and bushfire events of Australia in the past two years (2019-2020) (Cammelli and Angelsen, 2019; Glassey *et al.*, 2019; Lizundia-Loiola, Pettinari and Chuvieco, 2020; Yu *et al.*, 2020).

Regarding the markers for biodiversity change, driven by human activities, the global exchange of flora and fauna between the New and Old Worlds represents a key point in history that transformed global subsistence strategies, known as the "Columbian Biological

Exchange" (1450-1750) (Crosby, 1972, 2004). Due to its global impact on environmental change throughout the world, the Columbian Biological Exchange represents an important consideration regarding the onset of the Anthropocene, despite no geological stratigraphy markers being evident. The European conquest of the New World saw the expansion of crops that were once isolated to the region into Old Word territories. Maize (*Zea mays*) became increasingly used in colonial Africa, whilst tomatoes (*Solanum lycopersicum*), sweet potato (*Ipomoea batatas*) and cassava (*Manihot esculenta*) became well-established throughout Europe (Crosby, 2004; McNeill, 2003). The success of the Potato crop (*Solanum tuberosum*), sourced from South America, demonstrated the cultural revolution associated with the introduction of this staple, with sometimes dire consequences (see Irish Potato Famine (Haas *et al.*, 2009; Raffaele *et al.*, 2010). This exchange of plants and animals was not one way, with Old World ecological transformations also recorded in the New World. Records from the annals of convents in the old Aztec city of Tenochtilan indicates that the Spanish Conquistador Cortez gave direct orders to inhabitants to "plant trees from Spain" (Segura, 2018). Whilst this Europeanisation of the New World saw failures in the likes of olive and grape plants, success was also seen with Asian sugar cane, South East Asian banana and European wheat (Crosby, 2004; Segura, 2018). Along with these plants, animals typical of European farming methods, cattle, sheep and pig were introduced, whilst New World hens and roosters were managed by the Europeans (Crosby, 2004; Segura, 2018). The biological exchange between the New and Old World is not the only legacy of the European conquest, with disease and warfare resulting in the decline of the indigenous populations. With this "indigenous depopulation" (Loughlin *et al.*, 2018), the environments once occupied by large populations were left, recording vital information regarding the peoples who once managed them.

1:3 Environmental determinism and the "pristine" environments of the New World

The decline of indigenous peoples from the New World resulted in the abandonment of the environments they once lived. As researchers began to focus on these environments of the New World, questions began to be asked regarding the extent of influence these societies (here defined as pre-Hispanic) had on their environment. Environmental determinism represents a school of thought that places the environment (ecological and climate) as the main catalysts to human distribution, growth, decline and reorganisation (Hrebiniak and Joyce, 1985; Coombes and Barber, 2005). The New World environments represent an important region for the incorporation of environmental determinism in explaining how pre-Hispanic societies interacted with their environment.

The Amazon rainforest remains one of the most contested regions regarding the understanding of the impact of pre-Hispanic civilisations had on their environment. Early research suggested that the low-level populations of the Amazonia had limited impact on their environment, as they were primarily foraging communities (Meggers, 1954, 1971, 1993). According to these publications, the Amazon environment limited populations to grow, due to the poor soils and lack of available proteins, acting as a "counterfeit paradise" (Meggers, 1971)**.** As archaeological evidence began to show that large populations did occupy the Amazon forest (Hiraoka, 1980; Stokstad, 2003; Roosevelt, 2006), environmental deterministic hypothesis began to incorporate palaeoclimate records to link climate change with the collapse of populations, once again inferring how the environment limited population growth and sustainability (Meggers, 2001).

This evolution of environmental deterministic thinking, from limited forest impact to climate-driven collapse, is also evident in the case study the Ancient Maya Civilisation of Central America (*ca* 2500 BCE- 1550 CE/ 4.4 -0.4 kyr BP). Early research argued that the majority of the Maya Lowlands was an "area of limited agricultural production", where traditional slash and burn methods (here referred as *milpa*) supported small populations (Meggers, 1954; Cowgill, 1962), despite clear evidence for temple constructions in these tropical landscapes. Combinations of archaeological, palaeobotany and palaeoecological evidence began to highlight that the dense populations of the ancient Maya participated in

a range of agricultural techniques, with methods capable of maintaining large density populations (Lentz *et al.*, 1996; Dunning, Beach and Luzzadder-Beach, 2012; Kennett and Beach, 2013; Ford and Nigh, 2015). However, as environmental deterministic thinking again argued the environment limiting the growth of the ancient Maya, palaeoclimate records identified periods of intensive drought closely associated with a period of societal decline during what is now known as the Terminal Classic (750-1100 CE/ 1.2-0.8 kyr BP) (Hodell, Curtis and Brenner, 1995; Kennett *et al.*, 2012; Kennett and Hodell, 2017). Palaeoecologists have linked into this narrative of the environment heavily influencing the functionality of the ancient Maya populations, by suggesting large scale deforestation (Leyden, Brenner and Dahlin, 1998; Leyden, 2002; Dull, 2007) led to an ecological breakdown, resulting in the collapse of the civilisation (Shaw, 2003; Diamond, 2005)

Whilst environmental determinism played important roles in the development of our understanding of the environmental context of pre-Hispanic societies, research is beginning to show a more complicated picture regarding land-use strategies. The modern forests of Central and South America are now described in many areas of research as relicts of past agroforestry strategies (Heckenberger *et al.*, 2003; Ross, 2011; Lentz *et al.*, 2014; Ford and Nigh, 2015). Palaeoecological records are also informing how pre-Hispanic peoples managed the environment in different ways such as agricultural adaptions to improve drainage (Whitney *et al.*, 2014; Lomnardo *et al.*, 2013), management of wetland ecosystems (Beach *et al.*, 2009) and cultivation and management of the highly fertile seasonally dry tropical forests ecosystems through *milpa* agriculture (Carrillo-Bastos *et al.*, 2010; Nigh and Diemont, 2013).

1:4 Seasonally dry tropical forests

Seasonally dry tropical forests (SDTF) occur in the tropical/sub-tropical regions of the world, closely aligned to climates that receive between 500-1500mm in annual rainfall and also 5-8 rainless months (Pulla *et al.*, 2015; Sunderland *et al.*, 2015). SDTFs are particularly common in Sub-Saharan Africa, South Asia and South America, with distributions also in Central America and the Caribbean (Miles *et al.*, 2006; Pulla *et al.*, 2015). The majority of dry forest growth occurs during the wet season, with periods of growth slower during the dry season (Murphy and Lugo, 1996; Pennington, 2011). Soil composition variability also influences the potential composition of SDTF ecosystems, with hard leaf species (sclerophyllous type) more pronounced in shallow and infertile soils, whilst the deciduous forest species favour the deeper, fertile soils (Murphy and Lugo,

1996; Pennington, Prado and Pendry, 2000). Despite being located in similar tropical regions as rainforests, SDTFs remain largely under-represented in research (Pennington, 2011; Sánchez-Azofeifa and Portillo-Quintero, 2011; Pulla *et al*., 2015).

Seasonally dry tropical forests experience higher rates of deforestation compared to tropical rainforests (Murphy and Lugo, 1996; Miles *et al*., 2006; Vargas, Allen and Allen, 2008; Sunderland *et al*., 2015), with the low relief, fertile soils and diverse resources making these ecosystems valuable for non-timber related subsistence. Associated with their importance for land-use, SDTFs experience alarming rates of conversion to agricultural pastures, with Africa (20%), Central America (72%), South America (60%) and the Pacific islands (90%) the highest effected by conversions (Portillo-Quintero and Sánchez-Azofeifa, 2010; Aide *et al.*, 2013). Along with conversion to agricultural fields, anthropogenic impacts on dry forests see the introduction of invasive species, extraction of wood and introduction of fire into the disturbance regime severely affecting the sustainability of these ecosystems (Trejo and Dirzo, 2000; Dirzo and Mooney, 2011; Pulla *et al*., 2015). As SDTF exist in the same dry environments as savannah ecosystems, the threat of ecological transition, from a closed canopy dry forest to an open grass-dominated savannah is high, due to the consistent exposure of dry forests to human-induced fire activity (Pulla *et al.*, 2015). Changes in the inter-annual variability of rainfall and increasing time between the very wet and very dry years, driven by anthropogenic induced climate change, will see a range of responses for species within a dry forest ecosystem (Allen *et al.*, 2017). Increasing variability in precipitation may favour deciduous species in SDTF ecosystems, because of shorter functional time periods, whist increasing occurrence of short-term droughts will likely benefit the growth of SDTF species, although long term impacts of multi-annual droughts are less clear (Allen *et al*., 2017). Under increasing future drying, the drought-tolerant species will be particularly favourable in rainforest environments, providing highly fertile soils are present (Meir and Pennington, 2011). Regarding mitigation to climate change, seasonally dry tropical forests represent a carbon sink, storing up to 140 M per ha-1 (Vargas, Allen and Allen, 2008).

Whilst current anthropogenic threats represent a concern to the development and sustainability of seasonally dry tropical forests, these ecosystems were not only impacted by human land-use during the development of modern agriculture. Seasonally dry tropical forest ecosystems have been used extensively throughout time by pre-Hispanic cultures (Cooke and Ranere, 1992; Harrison, 1992; Roberts *et al.*, 2017). The South and Central American regions represent the best-developed understanding of seasonally dry tropical

forests usage by past communities, with the rich fertile soils allowing for the management of forest resources evidence from ethnobotanical and archaeological data (Gómez-Popa, Flores and Sosa, 1987; Primack *et al.*, 1998; White and Hood, 2004; Bonomo *et al.*, 2011).

Pre-Hispanic use of fire in seasonally dry tropical forests represents a crucial stage in the development of agriculture in these regions, with fire methods used to clear and manage the landscape to maximise agricultural output (Kleinman, Pimentel and Bryant, 1995; Daniels, Painter and Southworth, 2008; Nigh and Diemont, 2013). This past form of milpa agriculture has been developed/adapted in modern dry forest ecosystems. However, the development and demand for greater food production has increased the intensity of fire used in these systems along with the shortening of the recovery season for the forest (Urquiza-Haas, Dolman and Peres, 2007), making modern practices unsustainable. As humans have actively used fire management techniques in seasonally dry tropical forests over millennia, modern conservation strategies need to consider adaptions to current strategies and re-evaluate approaches that incorporate the past methods of land-use in these ecosystems.

As modern climate change will impact the frequencies and occurrences of fire in these ecosystems, past climate change has also been shown to introduce fire into these ecosystems, when modern humans were not present on the landscape. High-resolution charcoal records from an 86 kyr year-old sediment core have linked changing solar insolation patterns to fire frequency in seasonally dry tropical forest ecosystems in Guatemala (Lake Peten Itza) (Correa-Metrio *et al.*, 2012). Peaks in the fire record are closely associated with the Greenland stadial phase of climate change, linking wider scale climate oscillations to increasing fire occurrence in seasonally dry tropical forested ecosystems (Correa-Metrio *et al.*, 2012). These findings go against general consensuses of fire not being a feature of seasonally dry tropical forest ecology (Murphy and Lugo, 1996; White and Hood, 2004; Pennington, 2011), by showing that fire occurrence in these ecosystems is possible, when humans forcing is removed from the equation.

Along with the natural variability of fire regimes, past and present herbivore activity represents an important driver of vegetation change in seasonally dry tropical forest ecosystems. In the Santa Rosa National Park (Costa Rica), mammals such as tapirs and white-tailed deer both interact with the understory of the dry forest by consuming seeds and foliage (Bullock *et al.*, 1995). Leafcutter ants represent one of the major consumers of dry forest foliage, with their activity increasing during the dry season but also in human-

driven disturbances in the forest (Siquerira *et al.*, 2018). This is linked to increased productivity of the herbivores in a low resource site (Catimbau National Park, Brazil) (Siquerira *et al.*, 2018). Along with the direct impact on seasonally dry tropical forest vegetation (understory and foliage consumption), vertebrates also play an important role in the ecology of the ecosystems. Primates and bats represent important dispersers of seeds in seasonally dry tropical forest ecosystems (Lambert and Chapman, 2005; Lobova, Geiselman and Mori, 2009), with pioneer species of plants particularly well-represented in bats. Along with seed dispersal, bats also carry pollen with them on their long-distance travels and are responsible for pollinating over 500 plant types in the Neotropics (Dirzo *et al*., 2011). Complex relationships exist between the modern herbivore/vertebrates and seasonally dry tropical forest ecology, with the understanding of past relationships an important consideration for understanding how these relationships will change in the future.

Along with modern impacts on seasonally dry tropical forest, palaeontological records from Mexico have shown evidence for past herbivore activity and a potentially detectable signal in ecosystem change caused by grazing (Arroyo-Cabrales *et al*., 2010; Grimm *et al*., 2001). During the Pleistocene, the faunas of Mexico are shown to be diverse, with mega-herbivores and mega-carnivores inhabiting the regions (Arroyo-Cabrales *et al*., 2010). The Mexican Plateau was covered by grassland (Grimm *et al*., 2001), with openness in these ecosystems likely controlled by the presence of mega-herbivores such as mammoths, camels and bison (Arroyo-Cabrales *et al*., 2010). Without a human presence on the landscape, these mammalians and climate change were likely the dominant drivers of ecosystem change in Mexico. However, once humans began to populate the landscape, sometime during the last glacial-interglacial transition (Gonzalez-Gonzalez *et al*., 2010), these dominant herbivores were likely hunted as big-game for the early occupiers (Johnson *et al*., 2006).

As humans began to hunt the herbivores that dominated the Mexican region and likely other areas of Central America, vast ecosystem change resulted. The extinction of the mega-herbivores is attributed as a combination of human hunting and climate change (McGlone, 2012; Doughty *et al*., 2010). The removal of these species from the ecosystems, likely promoted ecosystem change throughout the region, with the pressure of extensive grazing reduced. However, the introduction of human methods of landscape modification (crop cultivation, fire, forest clearance for settlement) into the landscape began to alter the ecosystems of the Central American region. As humans began to remove and introduce

ecosystem pressures (remove herbivores, introduce fires and promote usable plant types), impact on seasonally dry tropical forests can likely extend back to their first period of habitation, *ca*. 10 kyr BP.

1:5 Approach

The ancient Maya are an important society to examine pre-hispanic land-use. Palaeoecological records have provided valuable insights regarding the degree of environmental impact associated with the ancient Maya, with this research using similar proxies (pollen and charcoal) to advance current understandings.

Palaeoecological research, focusing on ancient Maya environmental interactions, have shown a link between deforestation events (declining arboreal pollen) and population growth (Mueller *et al.*, 2010; Leyden *et al.*, 2002). This combination of evidence for population pressures driving environmental degradation has led to conclusions that ecological negligence played a pivotal role in the collapse of the Ancient Maya Civilisation, sometime between *ca* 750-1000 CE (Diamond, 2005; Shaw, 2003). Whilst the pollen evidence from the palaeoecological records clearly show declining abundances of tree pollen, there remains a gap in the understanding regarding the extent in which these activities were practised throughout the entirety of ancient Maya society. A sampling bias exists in the research, as the majority of interpretations of ancient Maya land-use are obtained from the larger temple regions of Central America, where the highest proportion of the population lived. Whilst these temple areas represent a crucial area of interest for understanding ancient Maya society, the low number of palaeoecological records that exist are often extrapolated to be representative of the entire society, when in reality they likely only represent one form of settlements. As a result, less attention is paid to how the lower-density settlements of the ancient Maya interacted with their landscape and if the claimed methods of environmental degradation are as extensive as suggested.

The Yucatan Peninsula has been chosen as the focus of this research, due to low spatial resolution of palaeoecological records from the region along with the high number of identified lower-density settlements (Leyden *et al.*, 2002; Villamil *et al.*, 2005). For this research, smaller density settlements were identified as locations that lacked large ceremonial architecture, such as temples, identifiable with ancient Maya “urban” populations. Secondly, land-use here is identified as practices that managed resources within the respective dry forest ecosystems, ranging from evidence for cultivation to the use of fire for forest management. Forest cover refers to the impact on trees recorded from the palaeoecological, measured through the relationship between arboreal and non-arboreal pollen.

From this investigation into land-use, greater insights regarding activities from coastal (Ambergris Caye) and the mainland (Laguna Esmeralda) will be provided. Seasonally dry tropical forests represent the environment in which the ancient Maya, of these smaller density populations, practised cultivation and impacted forest cover. The good soils and natural resilience of the ecosystems to drying will make these environments pivotal for understanding how climate change may have impacted ancient Maya land-use.

1:6 Research aim and questions

This research aims to use palaeoecological proxies to analyse how the ancient Maya used seasonally dry tropical forest ecosystems in lower-density settlements. By using high-resolution charcoal and pollen analysis, this research identifies periods of cultivation and associated impact on forest cover and improves the overall spatial resolution of palaeoecological records in the Yucatan Peninsula.

To address this research aim, the following questions are posed:

1- What were the land-use strategies of the ancient Maya in lower-density settlements in the coastal (Ambergris Caye) and the mainland (Quintana Roo) Yucatan Peninsula?
2- What impact on forest cover, associated with cultivation, is recorded from lower-density Maya settlement
3- Does the onset of cultivation from the palaeoecological records correlate with the archaeological record regarding initial occupation?
4- Do the palaeoecological records indicate increasing or decreasing land-use during drought conditions?

1:7 Thesis Organisation

The chapters of this thesis are presented as followed;

Chapter 2 provides a wider context for the study location. The modern environmental conditions such as climate and geology are discussed along with important features that have influenced Maya land-use. Palaeoenvironmental change from the late Pleistocene epoch to the Holocene is described, focusing on periods of climate change. Key archaeological changes, through the context of Maya cultural periods, are discussed to contextualise the societal pressures that would influence the subsistence strategies of the ancient Maya. Finally, to contextualise the current research and how it is interpreted regarding ancient Maya land-use, a discussion on the patterns of change from various palaeoecological proxies has been completed.

Chapter 3 provides the methodological approaches used to analyse data for *Chapter 4-6.* It describes the study sites along with outlining the protocol for the preparation and analytical techniques used for the palaeoecological records. This chapter also outlines how this research approached the analysis of surface sample data and how it can be compared to the modern landscape.

Chapter 4 presents the palaeoecological record from the island site of Ambergris Caye, the first attempt to use palaeoecological proxies to understand Maya land-use on an island site. A sediment core was extracted near the archaeological site of Basil Jones, were fossil pollen and charcoal proxies were analysed to frame ancient Maya land-use on the island.

Chapter 5 shows the palaeoecological record from the mainland site of Laguna Esmeralda. As part of a collaboration with colleagues from Nottingham University a high-resolution pollen and charcoal analysis was completed on the core.

Chapter 6 discusses the results from the surface sample analysis taken from Laguna Esmeralda and Lake Chichancanab. A series of samples from each lake were analysed to compare to modern calculations of forest cover to understand how such analysis can better inform the palaeoecological record from the respective lakes. A re-interpretation of a previous palaeoecological record from the Chichancanab core was completed.

Chapter 7 takes key themes from *Chapter 4-6* to highlight how this research has moved our understanding of ancient Maya land-use forward. This chapter also includes the conclusions of the thesis and how future work may be directed from the findings presented.

Chapter 2 Literature Review

2:1 Overview

In this chapter, the environmental characteristics of the Yucatan Peninsula are discussed within the wider regional scope of the Maya Lowlands, where the spatial variability of these parameters contributes importantly to the understanding of pre-Hispanic land-use. From a cultural and geographical perspective, the Ancient Maya Civilisation are the main focus of the thesis, who experienced numerous phases of societal growth and decline throughout their occupancy from *ca* 2500 BCE until Spanish contact in 1540 CE (*ca* 4.4-0.4 kyr BP). As these phases of growth and decline resulted in the movement of people throughout the sub-continent of Central America, a wider regional context of these cultural patterns is provided for the highlands and lowlands. To understand influences on the land-use strategies of the ancient Maya, cultural (growth and decline) and climate (increasing and decreasing dryness) context is given for a wider regional perspective (lowlands and highlands). These strategies will mainly be examined through palaeoecological records identifying various periods of cultivation and associated land-clearance along with changes in the palaeofire record to understand how fire was used by the ancient Maya for landscape clearance and subsistence management.

2:2 The Yucatan Peninsula

The Yucatan Peninsula is a carbonate platform that covers more than 150,000km^2, located in the northern part of the sub-continent of Central America (Bergoeing, 2015). The Central American continent is composed of the Yucatan Peninsula, Belize, Guatemala, El Salvador, Honduras and parts of Mexico (Chiapas) (Figure 2.1).

The Mexican States of Campeche, Yucatan and Quintana Roo, northern Guatemala and northern Belize make up the political borders of the Peninsula, along with the coastal islands. To the west, the Mexican state Chiapas is highlighted in Figure 2.1. Climate shows seasonal patterns in rainfall, resulting in a distinct wet and dry season, driven by the large-scale movements of the Inter-Tropical Convergence Zone. Soils throughout the Yucatan Peninsula are mainly composed of calcium carbonate, with shallow soils found throughout

the region. Surface water bodies throughout the Yucatan Peninsula are scarce, due to the porous characteristics of the limestone geology resulting in a deep-water table position. Rivers such as the Hondo (Belize), the Palzada and Candelaria (Campeche) and lakes such as Laguna Esmeralda and Lake Chichancanab are examples of such surface water features in the Yucatan Peninsula. Small lagoons and sinkholes represent opportunities to access below groundwater resources (Perry *et al.*, 1995; Fedick and Morrison, 2004; Islebe *et al.*, 2015).

2:3 The Maya Lowlands:

The Yucatan Peninsula is located in the northern region of the Maya Lowlands, with lowland areas of Guatemala and Belize composing the southern lowlands. The distinction between the Maya Lowlands and Highlands is based on topographic variations between the western and eastern regions (Figure 2.1). Further distinctions are based on variation in climate, hydrogeology and ecology, which closely control how per-Hispanic inhabitants managed the landscape.

2:4 Modern environmental parameters of the Maya Lowlands

2:4:1 Climate:

Large-scale climate dynamics in the Maya Lowlands are driven by variations in atmospheric circulation patterns such as the Hadley Cell and the North Atlantic Oscillation (NAO). The Hadley Cell circulation system transports air from the equator, poleward and acts between 30ºN and 30ºS of the equator (Gill, 2000; Hodell *et al.*, 2005; Gill *et al.*, 2007). Where the air rises at the thermal equator and descends at 15º, forms the Inter-Tropical Convergence Zone (ITCZ) (Figure 2.2). The Inter-Tropical Convergence Zone is a low-pressure belt that circles the Earth at the equator, where the northern and southern hemispheric trade-winds come together. The heat of the warm waters and intense solar radiation produces bands of thunderstorms as the humid air rises and expands. This phenomenon is responsible for the distinct seasonality in tropical rainfall experienced throughout the Maya Lowlands (Gill, 2000; Gill *et al.*, 2007; Pollock *et al.*, 2016). As the ITCZ, trade winds, and subtropical high-pressure belt are displaced northwards from the equator, the Maya Lowlands receives its maximum annual precipitation (Hastenrath and

Polzin, 2013). This peak in rainfall occurs between May-June and October-November with some regions seeing >1000 mm of rainfall across the rainy season (Jones *et al.*, 2016). As the ITCZ moves southwards, minimum rainfall amounts occur between January and April. Between the northern and southern lowlands, the north receives less precipitation per annum (500-1000mm) compared to south (1500-2500mm) (Figure 2.1). Associated to some degree with the Hadley Cell circulation system, the high-pressure cell in the North Atlantic Ocean (NAO) has been used to explain anomalies experienced in climate throughout time. The NAO is most evident in the region during the spring at the beginning of the rainy season (Giannini, Cane and Kushnir, 2001). A positive phase of the NAO, where the gradient between the Azores high and Icelandic Low-pressure system is greatest, results in stronger trade winds, reduced ocean temperatures and influencing precipitation patterns recorded in the Caribbean regions examined (Giannini, Cane and Kushnir, 2001). As this Azores high-pressure system moves southwest towards the Caribbean, it has been hypothesised that droughts have occurred, both past and present, in the Maya Lowlands (Hillesheim *et al.*, 2005). Temperature ranges in the lowlands are low throughout the year, ranging from ~25º-26ºC per annum (Torrescano-Valle and Folan, 2015) (Figure 2.1). The influence of warm waters from the Caribbean Sea and Pacific ocean results in a distinct hurricane season between June and October (Sanchez and Isleve, 2002; Adomat and Gischler, 2017), with on average one tropical storm or hurricane hitting the Yucatan Peninsula every year (Urquiza-Haas, Dolman and Peres, 2007).

2:4:2 Hydrogeology:

Access to surface water features is one of the key distinctions made between the northern and southern lowlands. The karst landscape of the northern lowlands, formed through the process of dissolution and erosion of the limestone bedrock, covers approximately ~154,000km^2 (23%) of the total Central American area (Kueny and Day, 2002; Bergoeing, 2015; Torrescano-Valle and Folan, 2015; Torrescano-Valle and Islebe, 2015). This geology promotes the drainage of rivers and streams deep underground throughout most of the northern lowlands, making access to these resources difficult. Sinkholes, a dissolution formation of the karst landscape, presents opportunities to access these deep-water tables. In the northwest Yucatan Peninsula, a 180km band of these sinkholes exist, known as the Ring of Cenotes (Perry *et al.*, 1995). Cenotes (derived from the Yucatec Mayan word *tz'onot* meaning natural well of water) are collapsed features that have occurred below the water table as a product of dissolution of limestone from water or as "dissolution lakes" (Perry *et al.*, 1995; López, 2008; Munro-Stasiuk and Manahan, 2010). Other existing

features of the landscape, anthropogenic and natural, result in differing adaptions to water management. An aguada (Mayan translation *dzadz*) is a collapse feature that touches, but not fully penetrates, the water table. Rejolladas (translation *ko'op*) are surface collapses that do not reach the water table and remain dry throughout the year (Munro-Stasiuk and Manahan, 2010; Munro-Stasiuk *et al.*, 2014). These features are found in the southern lowlands but due to the availability of surface water (such as rivers and streams), are thought to have been additional water resources for ancient peoples, features that may have been used during the dry season (Beach *et al*., 2012; Dunning, 1995).

In the southern lowlands, surface water is prevalent in the form of rivers and lakes. These features provided access to water resources for pre-Hispanic communities, which were particularly useful during periods of climate drying, with smaller streams increasingly used during these periods of drought (Harrison, 1993; Ford and Williams, 2007; van Hengstum *et al.*, 2010; Douglas *et al.*, 2015).

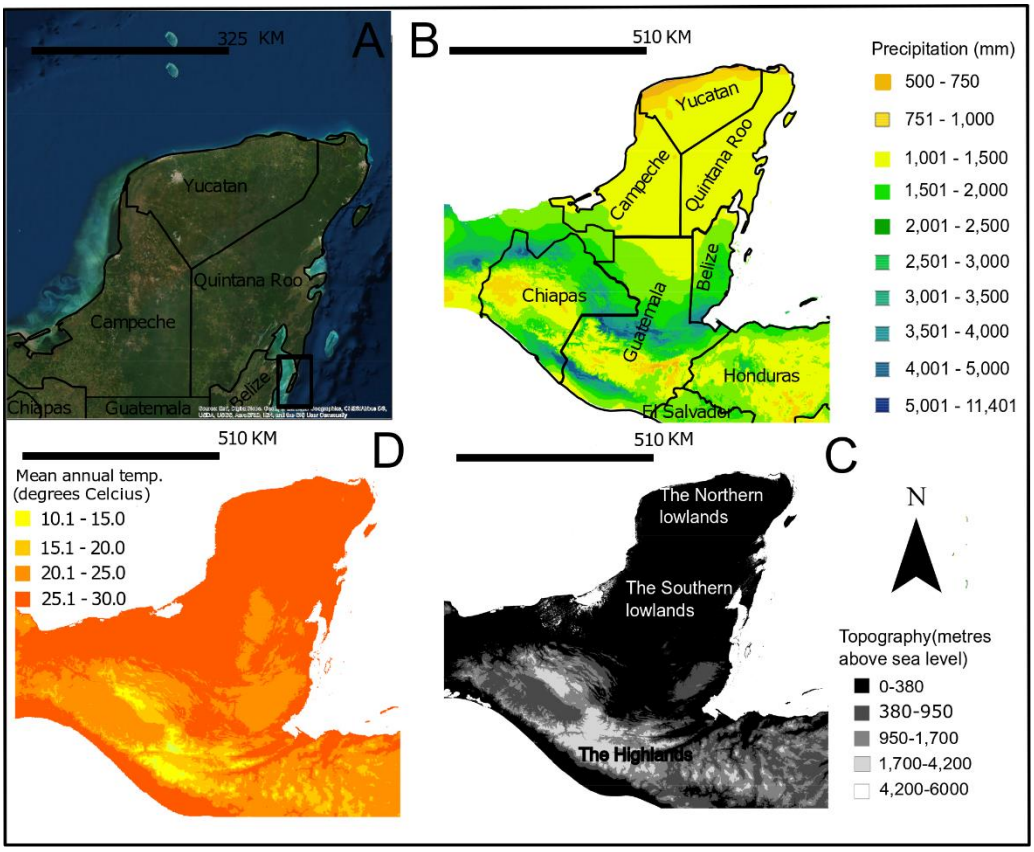

Figure 2.1 (A) Satellite image of the Yucatan Peninsula, highlighting the associated political districts. Black box indicates the island of Ambergris Caye. (B) Regional variations in mean precipitation per annum (mm) across Central America. Data extracted from the WorldClim climate project (Hijmans et al., 2005). (C) SEM elevation model of the wider Central American region, highlighting the Maya Highlands and Lowlands. Data provided by the Shuttle Regional Topographic Mission (SRTM). (D) Mean temperature variations per annum (°C), extracted from the WorldClim climate project (Hijmans et al., 2005)

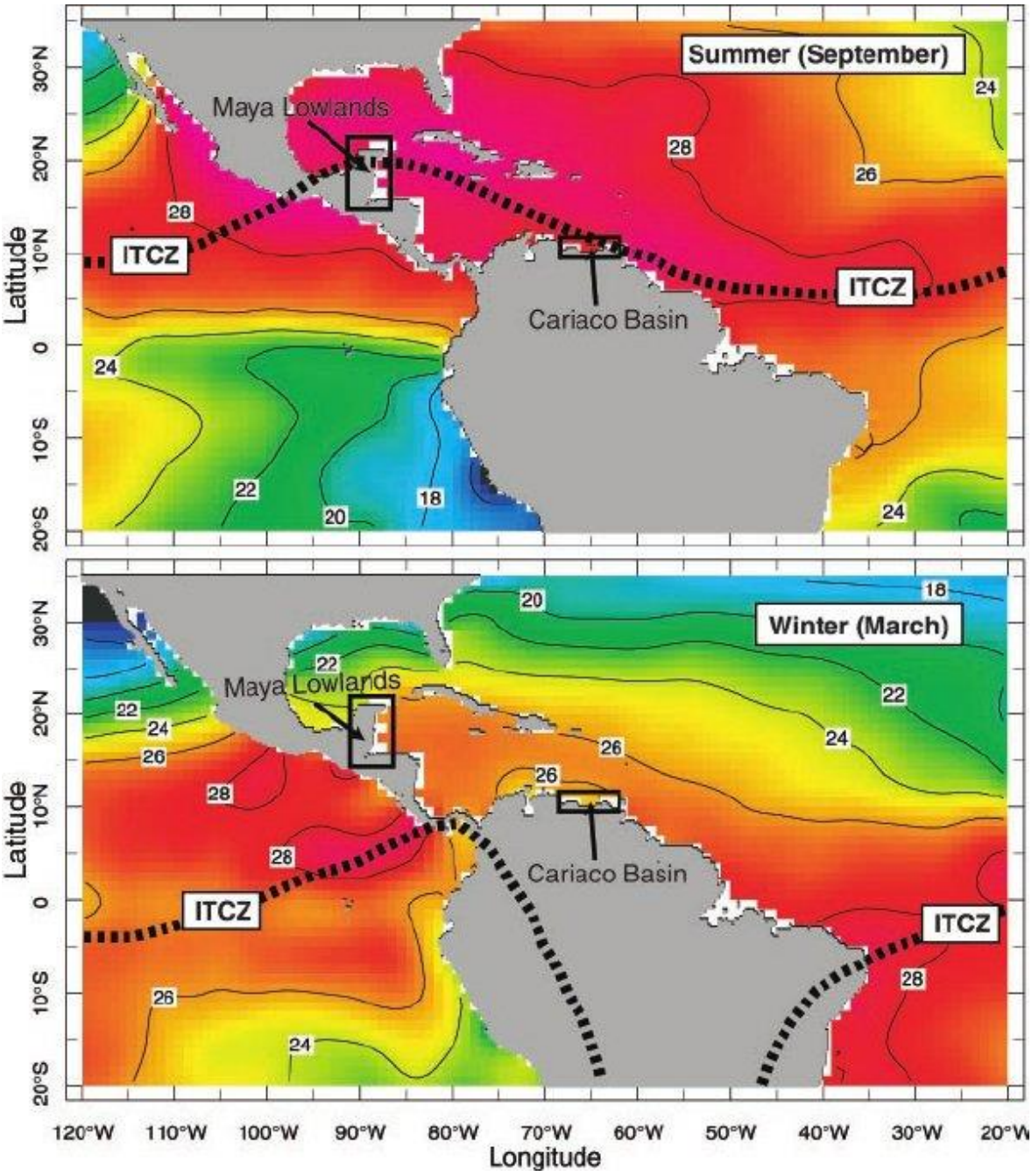

Figure 2.2 Mean position of the Inter-Tropical Convergence Zone illustrated for a typical summer (September) and winter (March). (Haug et al., 2003)

2:4:3 Regional variations in vegetation

The ecological diversity of the Maya Lowlands provides the environmental setting for understanding pre-Hispanic land-use in the region. The use of these diverse environments range from the use of wetland ecosystems, especially prominent in the southern lowlands (Beach *et al.*, 2009, 2019; Douglas *et al.*, 2015), to the use of dry forest ecosystems prevalent in the northern lowlands (Leyden, 2002; Carrillo-Bastos *et al.*, 2010). The

heterogeneity of ecology throughout the lowlands is primarily driven by the aforementioned climatic and hydrogeological gradients that exist. However, researchers have hypothesised that the composition of these ecosystems has been shaped by the land-use strategies of pre-Hispanic civilisations (Ford, 2008; Nigh and Diemont, 2013; Ford and Nigh, 2015), making a discussion of this variability crucial.

The dominant ecosystem in the northern lowlands is seasonally dry tropical forest, due to the lack of surface water availability and variations in precipitation per annum (Sánchez-Sánchez and Islebe, 2002; Hartter *et al.*, 2008) (Figure 2.3). Evergreen and semi-evergreen ecosystems also exist in northern lowlands, with precipitation controlling the degree of deciduousness experienced along a north-south gradient (White and Hood, 2004; Leyden, 2002). Along the coasts mangrove, wetland ecosystems and dune vegetation are controlled by their respective position to the water table and position from the sea (Fedick *et al.*, 2000; Espejel, 2012) (Figure 2.4). In the southern lowlands, the increasing influence of surface hydrological features results in deeper, fertile soils provided by river discharge (Meerman, 2005; Bhattacharya, Beach and Wahl, 2011). These features result in the development of deciduous broadleaf forests in regions such as Belize (Meerman, 2005) (Figure 2.5). Additional influences of these surface waters result in the development of swamp forests (“Bajos”), with mangrove ecosystems also prevalent along the coastal margins of the southern lowlands (Bhattacharya Beach and Wahl, 2011).

Figure 2.3 Seasonally dry tropical forests covering the catchment of Lake Chichancanab (Quintana Roo, Yucatan Peninsula) (January 2019).

Figure 2.4 Coastal mangrove ecosystems of southern Ambergris Caye, Belize. Front represents degraded mangrove caused by modern human clearance and the background shows a more developed mangrove ecosystem (July 2017)

Figure 2.5 Semi-deciduous broadleaf forest on the mainland of Belize (July 2017)

2:4:4 Seasonally dry tropical forests of the Yucatan Peninsula

Despite the rich diversity of ecosystems throughout the lowlands, this research focuses on the seasonally dry tropical forest of the Yucatan Peninsula and thus a more detailed examination of these environments is provided.

Seasonally dry tropical forests (SDTF) are distributed globally across Africa, Asia and the Americas, with vegetation constrained by degrees of precipitation, characterised by increasing deciduousness with decreasing precipitation (Pennington, Prado and Pendry, 2000; Gosling *et al.*, 2009; Pennington, Lavin and Oliveira, 2009; Pennington, 2011). From a palaeoecological perspective, differentiating between ecosystem types is imperative to understand how the environment changed in accordance with land-use. The seasonal dry environments in which SDTF ecosystems thrive also sees the development of savannah ecosystems. SDTF have high pH, deep fertile soils and are favourable for modern agriculture development (Pennington, Prado and Pendry, 2000; Pennington, 2011), compared to the poorer soils of savannah ecosystems. Species composition sees the dominance of perennial grasses in savannahs that are linked to consistent exposure to fire in these ecosystems, with grasses quick colonisers to recently burned landscapes. The exposure to these repeated fires results in the suppression of high canopy development (<10m canopy height in Belize) (Vieira and Scariot, 2006; Torrescano-Valle and Folan, 2015), with thick barks also representing natural adaptions to these fires in savannahs

(Dubbin, Penn and Hodson, 2006). Tree species characteristic of SDTFs does not contain these natural adaptive features to fire exposure, suggesting it did not play a role in the development of the ecosystems (Pennington, Prado and Pendry, 2000; Pennington, 2011). Although, whilst modern tree adoptions do not indicate a prevalence of fire activity in SDTF ecosystems, as previously mentioned long term records from the Yucatan Peninsula have indicated changes in fire activity in relation to long-term insolation records (Correa-Metrio *et al*., 2012).

The complex process of climate and human-induced impacts on SDTF ecosystems requires a deeper discussion. By nature, seasonally dry tropical forests have developed in response to changes between variations in precipitation between the wet and dry season, developing resilience to prolonged drying seasons. Longer rooting systems, timed flowering development (linked to the occurrence of the wet and dry season) and basal leaf structures (to maximise the water storage capacity) are examples of adaptations to efficiently maximise water resources in seasonally dry regions (Pennington, 2011; Pulla *et al.,* 2015). Hurricanes in the Yucatan Peninsula represent a natural hazard to the development of SDTF, causing relatively small reductions in forest basal areas with small trees particularly vulnerable to storm events (Urquiza-Haas, Dolman and Peres, 2007). Anthropogenic activities represent the greatest impact to SDTF ecosystems in the modern age. Degradation in seasonally dry tropical forest ecosystems is occurring at a faster rate than rainforests (Trejo and Dirzo, 2000; Miles *et al.*, 2006; Dexter *et al.*, 2015), with the fertile soils of SDTF particularly important for modern agricultural (Trejo and Dirzo, 2000; Lawrence, 2005). These environments have a long history of anthropogenic degradation and fragmentation, with the fertile soils driving inhabitants to transform the forests into agricultural pastures (Miles *et al.*, 2006).

The introduction of intensified fire regimes into the development of seasonally dry tropical forests has greatly influenced their sustainability. As previously mentioned, there are no natural tolerances to fire in these ecosystems, influencing the natural succession of species in the ecosystem (Vieira and Scariot, 2006). Whilst natural fires can occur in SDTF ecosystems, they are likely to spread from adjacent savannah ecosystems, with repeated exposure to fire resulting in a decrease in total area, due to the lack of recovery time associated with anthropogenic activities (Vieira and Scariot, 2006; Vargas, Allen and Allen, 2008; Pulla *et al.*, 2015). The use of traditional methods of agriculture (*milpa*) has increased the exposure of fire in these ecosystems (Miles *et al.*, 2006). By understanding

how these practices, which incorporate fires into the system, were used in the past we can gain a better understanding of how sustainable these practices may be in the future.

From a palaeoecological perspective, this dominance in perennial grasses in savannahs aids in the distinctions between SDTF ecosystems and savannahs, whilst the tolerance of SDTF ecosystems to high-frequency fire events, infers that savannah records would likely show higher concentrations of charcoal in the palaeoecological record, in scenarios void of human impact. Along with savannahs, moist tropical forests also share similar vegetation types as SDTF ecosystems, impacting how ecological groupings could be classified in the palaeoecological record. From phytolith assemblages of the Peten rainforest vegetation, species types such as *Brosimum alicastrum, Manilkara zapota* and *Vitex gaumeri* (Testé *et al*., 2020) are also shown in seasonally dry tropical forest plots in the Yucatan Peninsula (Islebe *et al.*, 2015) (Table 2.1). Wider forest-pollen analysis has also shown that family types of Combretaceae/Melastomataceae, *Cecropia, Alchornea,* Moraceae are present in SDTF, savannah and the respective moist tropical forest ecosystems (Correa-Metrio *et al*., 2011; Gosling *et al*., 2009). As previously discussed, species of the Poaceae family are dominant in wooded savannahs, Moraceae dominant in the moist tropical forests and *Anadenanthera* particularly dominant in SDTF ecosystems (Gosling *et al*., 2009). The combination of pollen trap data and vegetation surveying has greatly improved the resolution of inferring ecosystem qualities from the palaeoecological record, although increasing work can still be completed to improve the resolution of pollen identification to a sub-family level.

*Table 2.1:Main plant species of the seasonally dry tropical forest, savannah and rainforest ecosystems of the Yucatan Peninsula and Guatemala. Savanna and SDTF vegetation descriptions range from the multiple field surveys found in the literature (for example pine savannah, thickets, orchards), with the consistent major taxa identified here (Canche et al., 2018; Islebe et al., 2015; White and Hood, 2004; Bridgewater et al., 2002; Ibarra et al., 2002). Rainforest vegetation has been **identified** through modern vegetation surveys (Testé et al., 2020)*

Main plant Species of the seasonally dry tropical forests of the Yucatan Peninsula	**Main plant Species of the Savannahs of the Yucatan Peninsula**	**Main plant species of the rainforest ecosystems of the Peten forest, Guatemala**
Gymnopodium floribundum	*Pinus caribaea*	Burseraceae
Acacia sp.	Poaceae	Fabaceae
Bursera simaruba	Cyperaceae	Meliaceae
Lonchocarpus sp.	Asteraceae	Moraceae
Piscidia piscipula	Fabaceae	Sapindaceae
Manilkara zapota	*Ambrosia hispida* (Asteraceae)	Sapotaceae
Swietenia macrophylla	*Coccoloba uviferae*	Asteraceae
Pimenta dioica	*Acoelorraphe wrightii*	Pipertaceae
Chloraophora tinctoria	*Byrsonima crassifolia*	*Haematoxylum campechianum*
Sapindus saponaria	*Curatella americana*	*Laetia thamnia*
Vitex/*Caesalpina gaumeri*	*Chrysobalanus icaco*	*Pouteria campechiana*
Byrsonima bucidaefolia	*Ageratum radicans* (Asteraceae)	*Manilkara Zapota*
Spondias mombin	*Turnera diffusa*	*Protium copal*
Brosimum alicastrum	*Gliricidia sepians*	*Piscidia piscipula*
Ficus sp.	*Myrica cerifera*	*Spondias mombin*
Piper sempervirens	*Quercus oleoides*	*Lonchocarpus castilloi*

Metopium brownei	*Bucida buceras*	*Pimenta dioica*
Bauhinia jenningsii	*Haematoxylum campechianum*	*Brosimum alicastrum*
Mimosa bahamensis	*Eleocharis interstincta* (Cyperaceae)	*Vitex gaumeri*
Moraceae	Moraceae	Moraceae
Urticaceae	Urticaceae	Urticaceae
Celtis	Fabaceae	Celtis
Combretaceae	Combretaceae	Combretaceae
Melastomataceae	Melastomataceae	Melastomataceae

2:5 Palaeoenvironmental change in the Maya Lowlands

2:5:1 Pleistocene-Holocene climate transition

Palaeoenvironmental reconstructions for the Pleistocene epoch in the Maya Lowlands are limited as many of the lakes were not filled until *ca* 9 kyr BP, due to the influence of sea-level rise following the last deglaciation event (Szabo *et al.*, 1978; Metcalfe *et al.*, 2000). Long term palaeoclimate records from Lake Peten Itza has shown increases in fire activity *ca* 86 kyr BP (Correa Metrio *et al*., 2012), showing natural variability in the fire regime, likely driven by changes in large scale oscillation patters, with temperature decreasing between 86-20 kyr BP (Correa Metrio *et al*., 2012),. Between 50-10 kyr BP, the Peten Itza record identifies a link between the Greenland stadial and the North Atlantic ocean dynamics, resulting in peaks of fire activity, although local vegetation likely also had an important contribution (Correa Metrio *et al.*, 2012).

Continuing in the southern lowlands, between *ca* 34-24 kyr BP lakes from Guatemala (Lake Quexil and Peten Itza) were lower than present, with montane taxa abundances such as *Pinus* and *Quercus* interpreted as evidence for a cooler climate (Leyden *et al.*, 1993;

Hillesheim, *et al.*, 2005). In Guatemala, the Lake Quexil vegetation reconstruction indicates that temperatures between 24-14 kyr BP were 5-8 °C cooler than present (Leyden *et al.*, 1993). This climate record is based on the dominance of species that are currently found at altitudes higher than 1500m today (Leyden *et al.*, 1993). From *ca* 12 kyr BP, drying decreased following the deglaciation event, with Lake Quexil rapidly infilling at ~10.5 kyr BP and the first appearance of tropical rainforest at *ca* 9 kyr cal. BP associated with increasing temperatures and precipitation (Leyden, 1993; Hillesheim, *et al.*, 2005).

2:5:2 Holocene palaeoenvironmental change

The introduction of anthropogenic drivers complicates the climate-based interpretations of vegetation change in the palaeoecological record. As land-use will be discussed in depth later in this chapter, this section will primarily focus on key periods of climatic change and its influence on ecological change during the Holocene. Following deglaciation, much of the lowlands experienced increases in precipitation at *ca* 11 kyr BP. This resulted in the expansion of rainforest vegetation, along with additional archival sources for palaeoecological interpretations due to the infilling of the lakes in the Peten district (Leyden, 1984; Hillesheim *et al.*, 2005). Many of these lakes infilled between 10.5-8.0 kyr BP (Hodell, Curtis and Brenner, 1995; Curtis *et al.*, 1998; Wahl, Byrne and Anderson, 2014). Regional variations in climate are recorded throughout the lowlands, with records indicating increased precipitation from as early as 9.5 kyr BP, with increasing dryness as early as 7.5 kyr BP (Figure 2.5). This drying trend continued throughout most of the Holocene, with regional signals disagreeing between the onset of this drying trend (Hodell, Curtis and Brenner, 1995; Curtis *et al.*, 1998; Wahl, Byrne and Anderson, 2014). At *ca* 1 kyr BP, all regional palaeoclimate records show a period of drought.

In Hillbank lake, Belize, diatom records indicate lower water levels driven by drying periods between 11.3-11.1 kyr BP (Metcalfe *et al.*, 2008). Between 9-8 kyr BP, palaeoecological records indicate that rainforest taxa (Moraceae) are dominant throughout Guatemala, driven by these periods of increasing precipitation (Deevey *et al.*, 1979; Leyden, 1984; Vaughan, Deevey and Garrett-Jones, 1985; Leyden *et al.*, 1993; Islebe *et al.*, 1996). A shift to open vegetation, between 6-4 kyr BP, has been interpreted to represent climate drying in Guatemala, although speleothem records from Belize indicate a relatively wet climate between this period (Pollock *et al.*, 2016). These differences could be explained by regional variations in climate between Guatemala and Belize, or potentially be local changes in vegetation in Guatemala against regional-scale changes in

climate from Belize. Oxygen and carbon isotopic analysis from Lake Chichancanab, in the northern lowlands, also support the Macal Chasm speleothem, indicating relatively wet conditions between 6-4 kyr BP (Hodell, Curtis and Brenner, 1995; Hodell *et al.*, 2005). The El Palmar swamp area, between the Quintana Roo and Belizean border, shows a shift from secondary forest vegetation to increases in mangrove assemblages, interpreted to reflect sea-level rise during this period (Islebe *et al.*, 2006), which is also recorded on the coastal island of Ambergris Caye, where sea level rose approximately 4 metres between 6-3 kyr cal. BP (Dunn and Mazzullo, 1993). In the northern lowlands, a shift is recorded to more open vegetation change and declining forest taxa between 3.8-1.3 kyr BP (Leyden, 2002).

As strong associations are made between the occurrence of drought events and the collapse of the ancient Maya, palaeoclimate records have been produced at higher resolutions than other regions, to try and closely correlate drought events to periods of population instability. Between *ca* 1.7-1.0 kyr BP, two periods of intensive drought are recorded (Turner and Sabloff, 2012; Torrescano-Valle and Islebe, 2015; Kennett and Hodell, 2017; Brenner, Mark. *et al.*, 2018). At 1.7 kyr BP, a period of drought is recorded in the southern lowlands from the Chen Ha Cave speleothem (Pollock *et al.*, 2016), with the Yok Balum record showing a drying signal although not discussed in the research (Kennett, *et al.*, 2012). The Río Secreto speleothem, in coastal Quintana Roo, produces a higher resolution reconstruction of this drought event compared to the lake records (Punta Laguna, Chichancanab) (Medina-Elizalde *et al.*, 2016). The record indicates that two periods of drought events occurred between *ca* 1.75-1.71 kyr BP (CE 186 and 232) lasting 31 and 22 years respectively (Medina-Elizalde *et al.*, 2016). The next drought event, recorded at ~1.0 kyr BP is recorded across all palaeoclimate records in the Maya Lowlands (Hodell, Curtis and Brenner, 1995; Hodell *et al.*, 2005; Webster *et al.*, 2007; Kennett *et al.*, 2012; Medina-Elizalde *et al.*, 2016), with research indicating precipitation reductions up to 70% during this period (Brenner *et al.*, 2018).

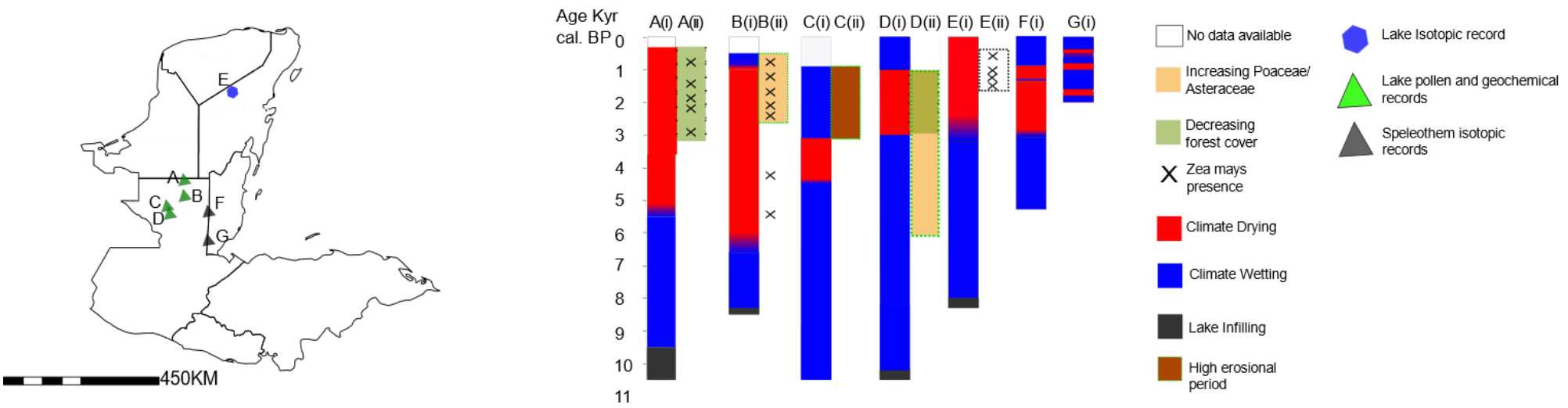

Figure 2.5 Illustration of palaeoenvironmental change and human impact driving vegetation change over various sites in the Maya Lowlands from 10.5kyr BP; (i) Represents the palaeoclimate change whilst (ii) highlights the anthropogenic impacts. (A) Lake Paixban (Wahl *et al*., 2016) using pollen and geochemical analysis (proxies: C: N ratios, Total organic matter, CaC03, non-carbonate organic and magnetic susceptibility); (B) Lago Peurto Arturo (Wahl *et al*., 2014) using pollen and geochemical (proxies: particle density, CaC03, total Organic matter, non-carbonate organic, magnetic susceptibility); (C) Lake Petén Itza Northern Basin (Curtis *et al*., 1998) using pollen and geochemical (proxies: magnetic susceptibility); (D) Lake Petén Itza Southern Basin (Curtis *et al*., 1998); (E) Lake Chichancanab using lake isotopic proxies (Hodell, Curtis and Brenner, 1995); (F) Macal Chasm Speleothem (Akers *et al*., 2016) using speleothem isotopic proxies. (G) Yok Balum Speleothem using speleothem isotopic proxies (Kennett *et al*., 2012). Blank boxes illustrate unavailable data.

2:6 The ancient Maya civilisation

The advances in the understanding of the ancient Maya long count calendar has allowed for inscriptions inbuilt monuments to be translated into Georgian calendar chronologies (BC/AD). To respect these crucial advances in ancient Maya archaeology the discussion of the civilisation will be examined by using BCE and CE chronologies. Similarly, as patterns of migration throughout the wider region play an important role in the understanding of land-use, the wider regional (highlands and lowlands) archaeological context will be provided. The ancient Maya civilisation occupied areas throughout the highlands and lowlands of Central America from *ca* 2500 BCE until the first contact with the Spanish colonisers in 1540 CE. The term "ancient Maya" is assigned to numerous pre-Hispanic Central American socio-political groups, who offered a great deal of cultural variation throughout the region (Lohse, 2010). Despite these discrepancies in languages and ethnicities, the term "ancient Maya" will refer to the human culture on the landscape of the Maya Lowlands and Highlands from *ca* 2500 BCE until Spanish contact in 1540 CE.

Throughout ancient Maya presence in Central America, periods of cultural growth (Iannone, 2014; Munro-Stasiuk *et al.*, 2014; Cucina, 2015; Lentz *et al.*, 2018) and decline (Diamond, 2005; Iannone, 2014; Villamil and Sherman, 2017) are preserved in the archaeological record, with climate change a consistent narrative regarding the drivers of these cultural declines (Hodell, Curtis and Brenner, 1995; Gill *et al.*, 2007; Hodell, Brenner and Curtis, 2007; Carrillo-Bastos, Islebe and Torrescano-Valle, 2013; Kennett and Hodell, 2017). The cultural context of the ancient Maya provides valuable insights regarding the land-use strategies of their civilisation. As the civilisation grew, sustained large populations and declined, varying degrees of forest clearance are recorded in the palaeoecological record. Therefore, by discussing the cultural processes that were present on the landscape throughout the occupancy of the ancient Maya, a greater insight into the drivers of land-use can be determined. Furthermore, the dynamic relationship between the ancient Maya and their environment is an important theme of this research and therefore, the previous palaeoclimate interpretations will be referenced against key archaeological periods.

2:6:1 The Archaic *ca* 7000-2500 BCE

The ancient Maya were not the first culture to occupy Central America. Artefacts of fluted points and projectiles found throughout the highlands and lowlands are linked to

Palaeoamerican, hunter-gatherer, populations (Brown, 1980; Valdez and Aylesworth, 2005; Gonzalez-Gonzalez *et al.*, 2008). More closely related to the ancient Maya, the Olmec civilisation constructed permanent settlements throughout mainland Mexico (Byrne and Horn, 1989; Grove, 1997; Wendt, 2010; Gillespie and Volk, 2014). The difficulty in understanding the transition between the hunter-gatherer archaic phase and the permanent settlements of the Preclassic comes from the aforementioned limitations associated with ethnic associations. Archaeologists have used ceramics and linguistics to understand how the ancient Maya developed, but in a phase of little ceramic production, the Archaic period is less clear than the following cultural era. (Lohse, 2010). During this period, climate conditions were generally wetter between *ca* 7000-3000 BCE (Wahl *et al.*,2014; Curtis *et al*., 1998; Hodell, Curtis and Brenner, 1995), with a drying climate recorded in Guatemala from 3000 BCE (Wahl *et al.*,2014; Curtis *et al*., 1998)

2:6:2 The Preclassic *ca* 2500 BCE – 200 CE

The transition from the pre-Maya culture, likely Palaeoamerican, into the permanent settlements of the ancient Maya culture was not a quick transition across the highlands and lowlands. The best evidence for these permanent settlements comes from the western Pacific coast, ranging from Chiapas (Mexico) to western parts of El Salvador (Voorhies and Kennett, 1995; Coe, 2015). In Soconusco, Mexico, the archaeological perspective suggests permanent settlements in the area by *ca* 1800 BCE (Voorhies and Kennett, 1995), with the inhabitants potentially using inundated bajos (seasonal wetlands) to increase agricultural output, with pottery becoming more sophisticated between 1800-1500 BCE (Coe, 2015). These permanent settlements saw some degree of hierarchical clustering, suggesting larger villages containing populations greater than 1000 peoples (Arroyo, 1995; Kosakowsky, Francisco and Pettitt, 2000; Coe, 2015). In the mainland of Mexico, the Olmec civilisation continued to grow, with the site of San Lorenzo becoming well established as a political centre for the population occupying the region from *ca* 2000 BCE (Grove, 1997; Wendt, 2010; Glascock *et al.*, 2013; Inomata *et al.*, 2013; Gillespie and Volk, 2014; Pool and Loughlin, 2017). However, the *collapse* of San Lorenzo, *ca* 1200 BCE, saw the movement of Olmec people throughout the Pacific coast settlements, with their influence recorded through pottery evidence (Blomster, Neff and Glascock, 2005; Coe, 2015). These early forms of permanent residencies and sophisticated pottery have not yet been found in the along the eastern Caribbean coast, with the settlement expansion during the Middle Preclassic (*ca* 400 BCE) the earliest date for these developments in the eastern region (Coe, 2015). The development of major Preclassic centre Kaminaljuyu, in

the highlands of Guatemala, was established and thriving towards the Late Preclassic (Coe, 2015; Love, 2018). From the lowlands, Preclassic centres such as Tikal (Laporte and Fialko, 1995), Uaxactun (Aimers, 2007) and Lamanai (Pendergast, 1982) became well established in this period. From a wider palaeoclimate perspective, climate drying continuous around the lowlands recorded from lake records (Wahl *et al*., 2016; Curtis *et al.*, 1998; Hodell *et al.*, 1995) from *ca* 3000-1000 BCE, with speleothem records from Belize recording a highly variable shift between wetting and drying (Figure 2.5) (Akers *et al*., 2016; Kennett *et al*., 2012; Webster *et al*., 2007)

Whilst the Preclassic is thought of as a significant period of development in Maya culture, with architectural styles becoming increasingly complicated and extravagant towards the latter stages of the era, a period of political disruption occurred throughout the lowlands *ca* 150-250 CE. During this time numerous sites throughout the region were abandoned, with a great deal of heterogeneity complicating the understanding of this abandonment (Aimers and Iannone, 2014; Coe, 2015; Lentz *et al.*, 2018). In Guatemala, within the Mirador Basin alone, numerous settlements were abandoned, whilst others continued to develop and grow into the Classic era. Sites such as San Bartolo were abandoned, yet a nearby site of Xultun continued into the Classic Period (Garrison and Dunning, 2009). In Belize, sites within the Tree Rivers region continued to develop and showed no sign of abandonment, suggesting a relationship between a sites proximity to water availability and continuity of occupation (Iannone, 2014). Similarly in the Yucatan Peninsula, sites that had greater access to surface water continued to develop into the Classic with others being abandoned that had limited access (Dunning *et al.*, 2014). The hypothesis regarding the importance of water resources during this period is underlined by the occurrence of an intensive drought period recorded in various paleoclimatic archives (Webster *et al.*, 2007; Medina-Elizalde *et al.*, 2016). Whilst drought likely had a significant impact on the ancient Maya during this period of development, the site variability of abandonment highlights the heterogeneity of impact throughout the Maya occupancy region. Investments into hydrological architecture at sites, such as Edzna, indicates some degree of adaption to these drought conditions to minimise future impact (Coe, 2015). The highlands never recovered to the extent previously seen with the capital site, Kaminaljuyu, abandoned by 150 CE (Love, 2018).

2:6:3 The Classic Maya *ca* 200-800 CE

The Classic Maya period is identified in the archaeological record as the time span in which the ancient Maya began to incorporate the long count calendar into the construction

of their architecture (Coe, 2015). The process of deciphering these calendar dates has allowed for a high-resolution chronological record associated with the construction, political activities and warfare. The Classic is seen as a period of major population growth, the construction of sophisticated temples, organisation of people into almost political roles (such as kings, nobles, ambassadors and servants) and warfare throughout the region (Chase and Chase, 1989; Demarest *et al.*, 1997; Palka, 2001; Aoyama, 2005; Coe, 2015). The Classic is divided between the Early Classic (*ca* 200-600 CE) and the Late Classic (*ca* 600-800 CE). This divide likely links to the extent of influence recorded across the lowlands of the Mexican urban centre of Teotihuacan (Manzanilla *et al.*, 2008). Teotihuacan was founded *ca* 200 BCE, a military power controlling trading in the north, evident from centres as south as Copan (Honduras) (Aoyama, 2001; Manzanilla *et al.*, 2008; Chase and Chase, 2011), until its demise between 600-700 CE (White, Longstaffe and Law, 2001; Manzanilla *et al.*, 2008; Chase and Chase, 2011). In the Late Classic, regional capital centres such as Tikal (Lentz, Dunning and Scarborough, 2015; Lentz *et al.*, 2018) and Caracol (Chase and Chase, 1989, 2001, 2016) were prominent in the southern lowlands, whilst Calakmul (Folan *et al.*, 1995) and Coba (Leyden, Brenner and Dahlin, 1998; Folan *et al.*, 2009) were strong establishments in the northern lowlands. The site of Tikal offers an interesting narrative to discuss a possible "hiatus" during the Classical Period. Between 534-593 CE, construction at Tikal ceased, with the archaeological record identifying numerous centres around Tikal being potentially impacted (Iannone, 2014). However, similar to the Preclassic abandonment period, the timing of this event was not uniform throughout the lowlands (Moholy-Nagy, 2003), emphasising once again the heterogeneous nature of societal abandonments.

The palaeoclimate records from the Classic Period continuous to show drying throughout this time of major political and societal development from the lake isotopic records (Wahl *et al*., 2016; Curtis *et al.*, 1998; Hodell *et al.*, 1995), which could have important implications regarding the understanding of the capability of the ancient Maya to adapt to drying conditions. Questions must be asked if a society developed during a prolonged drying event, as evident from the palaeoclimate records, then how sensitive was their society to abrupt intensifications of these drying events. Unfortunately, regional signals vary regarding the length of this prolonged drying, Lake Paixban and Lago Peurto Arturo showing it continues for the whole of the Classic period, whilst Lake Peten Itza (Wahl *et al*., 2016; Curtis *et al.*, 1998) shows a wetness signal (Curtis *et al*., 1998). Speleothem records and northern lake records also show varying degrees of dryness (Akers *et al*., 2016;

Hodell *et al*., 1995) and wetness (Kennet *et al*., 2012) recorded at the start of the Classic Period ~200 CE (Figure 2.5)

2:6:4 The Terminal Classic *ca* 750-1100 CE

The Terminal Classic has been a primary focus in ancient Maya research studies, due to the evidence indicating a substantial period of societal *collapse* (Demarest, 2004; Aimers, 2007; Douglas *et al*., 2015). The temporal and spatial heterogeneity of the *collapse* period throughout Central America has been termed a period of "critical transition" (Scheffer, 2009), whereby many political capitals throughout the region experienced a cessation in construction and site abandonment (Aimers, 2007; Iannone, 2014). This definition for collapse was chosen due to the evidence for wider societal impacts during this period. Along with the cessation in construction, pottery styles changed, large settlements were abandoned, and populations moved towards the coast following this period. The inter-site variability that shows sites thriving during the Terminal Classic, indicates that the period was a period of transition, rather than collapse.

In the southern highlands, one of the first sites to be permanently abandoned following the substantial growth of the Classic era was the site of Ceren in Honduras. However, cultural process can be removed as a driver of abandonment in Ceren, as the settlement was consumed by volcanic ash following the eruption of Ioma Caldera in 650 CE (McKee and Sheets, 2003). In Guatemala, the abandonment of major centres of Tikal and Uaxactun occurred by the 9th century CE, with Uaxactun never reoccupied (Valdés and Fahsen, 2004; Aimers, 2007). In Belize, a greater inter-site variability exists, with smaller settlements located close to surface water (such as Lamanai and sites within the Tree Rivers Region) continuously occupied throughout the Terminal Classic (Pendergast, 1982; Walker, 1990; Andres and Pyburn, 2004; Masson, 2015), whilst regional centres Xunantunich and Caracol were abandoned between the 8-9th centuries (LeCount *et al.*, 2002; Aimers, 2007; Coe, 2015).

The Terminal Classic in the northern lowlands highlights a similar pattern of inter-site variability, where numerous sites expanded, declined and continued throughout the Terminal Classic (Aimers, 2007; Aimers and Iannone, 2014; Coe, 2015). In previous archaeological research, this period (*ca* 750-1100 CE) is often seen as an extension of the Late Classic period, but recently the same nomenclature has been applied throughout the northern lowlands. Throughout the region, many centres experienced a period of decline between 900-1000 CE, almost two centuries after the experiences in the southern lowlands

(Carmean *et al.*, 2004; Demarest *et al.*, 2004; Aimers, 2007). However, the political centre of Chichen Itza, grew in stature during this period, reaching its peak between 800-1000 CE (Hoggarth *et al.*, 2016). Also seeing major societal growth, urban areas sites such as Uxmal, Oxkintok, Kabah and Sayinl peaked during the Terminal Classic (Carmean, Dunning and Kowalski, 2004; Demarest and Rice, 2004; Aimers, 2007). Centres such as Ek Balam fell to the growing powers of Chichen Itza following periods of warfare, with sites such Uxmal showing extensive evidence for barricade architecture (Dahlin, 2000; Aimers, 2007).

Due to the spatial and temporal heterogeneity of this period of transition recorded throughout the highlands and lowlands of the Maya area, a single sole issue cannot explain fully why this event occurred. Broadly speaking, warfare (Demarest *et al.*, 1997; Dahlin, 2000; Palka, 2001; Aoyama, 2005) and environmental causes (Hodell, Curtis and Brenner, 1995; Curtis, Hodelle and Brenner, 1996; Shaw, 2003; Diamond, 2005; Dull, 2007; Turner and Sabloff, 2012; Hoggarth *et al.*, 2016) are linked to the demise of many centres, with the latter particularly important regarding the land-use strategies of the ancient Maya. The complex relationship between internal societal dynamics (economics, migration, warfare, population growth) and external environmental conditions (climate change) are most prevalent under the scope of land-use strategies, which acts as the intersection were both these dynamics meet.

2:6:5 The Postclassic *ca* 900-1540 CE

The Postclassic is often defined as the era following the Terminal Classic and continues until the arrival of Spanish invaders in the 16th century CE. The Postclassic is separated from the aforementioned periods because monuments constructed no longer use the long-count calendar (Chase and Rice, 2014), making the timing of its occurrence difficult to pinpoint. The great Terminal Classic state of Chichen Itza fell to external invasion (possible external cultures such as the Toltecs) as a combination of Maya and foreign culture is reflected in building architecture, with the construction of the *Castilla* (church) built in the latter half of the 10th century (Coe, 2015). In 1263 CE, the site of Mayapan was founded in the Yucatan, potentially by immigrants from Mexico, struggling to find settlement elsewhere (Coe, 2015; Ledogar, 2018), although settlement in the region, before the cities development, is dated to the Preclassic (Milbrath and Lope, 2003). During the Postclassic, trading becomes particularly prominent along the Yucatan coast (Kepecs and, MacKinnon 1989; McKillop, 1996; Chase and Rice, 2014; Simmons and Graham, 2017) as settlement along this area signifies its growing importance (Chase and Rice, 2014; Iannone, 2014). In the southern lowlands, settlements that were continuously occupied during the Terminal Classic, such as Lamanai (Pendergast, 1982; Hanna *et al.*, 2016), continue to prosper along riverine locations (Chase and Rice, 2014; Coe, 2015). This focus towards coastal and riverine settlements provided marine-based resources for the ancient Maya to use as an alternate strategy to arable farming (Williams, White and Longstaffe, 2009). As previously mentioned, the dynamic trade centres of the coastal Caribbean allowed for long-distance trade of a variety of subsistence. Trading in exotic goods such as pottery and obsidian was prominent with the coastal areas also engaging in salt processing (Kepecs and MacKinnon 1989; Guderjan, 1995; McKillop, 1996, 2010; Cucina, 2015), with island sites such as Ambergris Caye and Cozumel seeing increased activity during the Postclassic.

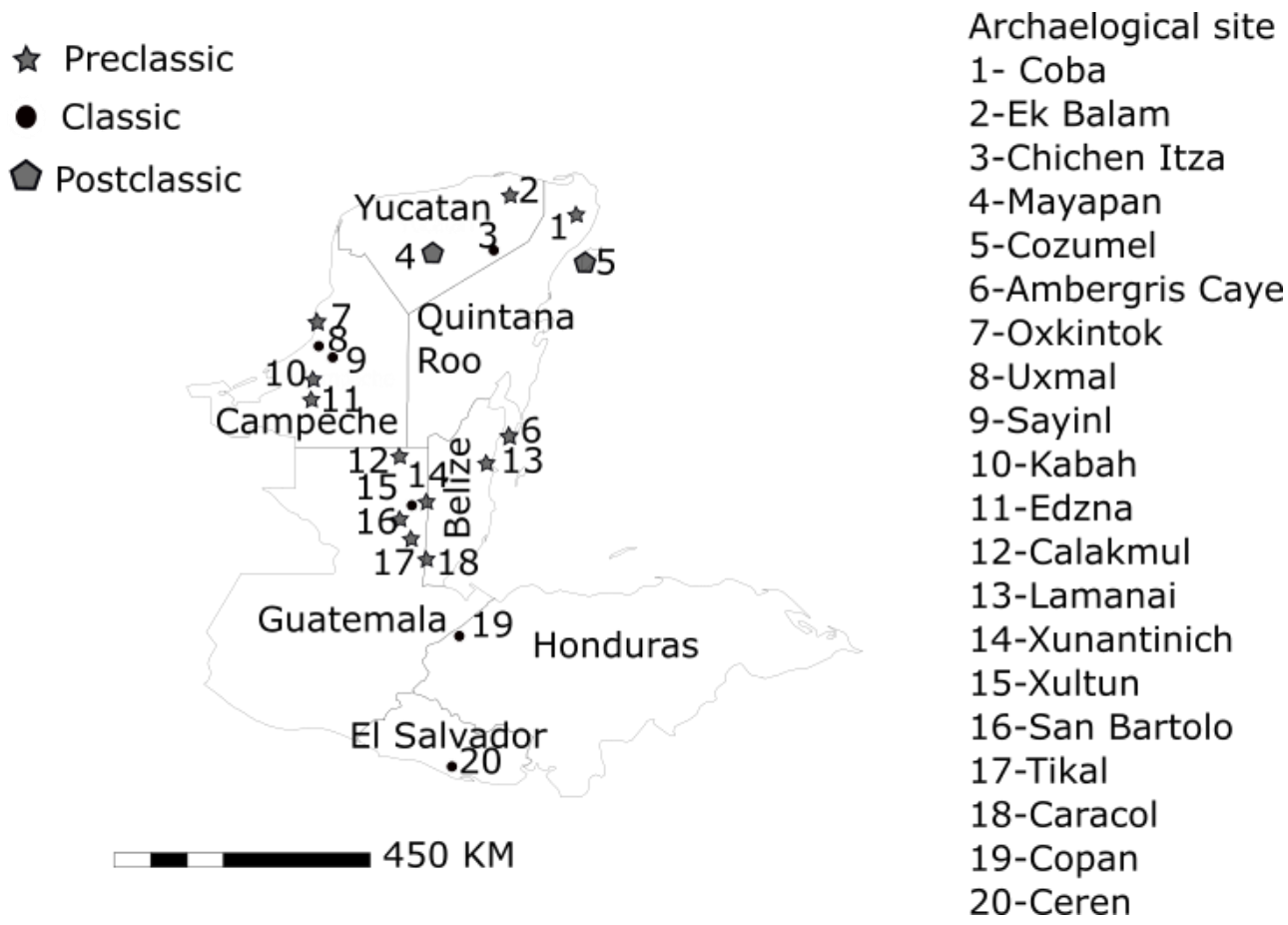

Figure 2.6 Archaeological sites of the Maya Highlands and the Lowland showing sites mentioned in the text. The island sites of Cozumel (1) and Ambergris Caye (18) are also shown. Symbols reflect the time of occupation.

2:7 Land-use strategies of the ancient Maya

Land-use strategies are defined here as the modification of the landscape to provide subsistence and resources for the ancient Maya inhabiting a region. Subsistence, from a land-use perspective, involves the planting of crops to support varying sizes of populations, although consumption of fruit and marine resources likely also acted as forms of subsistence. Resource management involves the selective management of important species for economic/cultural purposes such as trees used for shade or certain trees whose timber was used for construction. Both subsistence and resource management have forms of techniques used to modify the landscape, which is detectable in the palaeoecological record. From ecological and historical perspectives, evidence for ancient Maya land-use is mainly examined through palaeoecological proxies. As sites in the southern highlands (Honduras and El Salvador) (McNeil, 2012; Dull, 2004, 2007) provide important land-use context, their inclusion in this discussion of lowland ancient Maya is justified.

2:7:1 Ancient Maya plant use

Cultivation of staple crops such as maize, manihot and squash were not the only methods of land-use performed by the ancient Maya. The diverse tropical forests of Central America provided the opportunity for the society to diversify their land-use strategies, through the use of economically important plant species. These species likely played a crucial role in the lifestyle of the ancient Maya, providing various services for the peoples in addition to traditional crops.

Ethnobotanical research into the use of economically important plant species by the ancient Maya has examined the modern Maya society and interpreted that the peoples who use the forests today have adapted their strategies from ancient Maya traditions (Ford, 2012; Ross, 2011; Ross and Rangel, 2011; Ford, 2008). Modern commercial use of plants by the Maya people, such as vanilla (*Vanilla planifolia*) and cacao (*Theobroma cacao*) are grown both in the forests of Central America and the individuals' gardens, termed "forest gardens" (Ford, 2011; Ford, 2008). These forest gardens are instrumental to arguments that indicate that the ancient Maya promoted biodiversity and used a wide range of forests resources other than simply crop cultivation. According to ethnobotanical surveys of modern Maya forest gardens, plants were used for multiple functions by the ancient Maya (Ford, 2011;

Ford 2008). Dominant plants in these forest gardens include *Spondias mombin* (food, medicine), *Bursera simaruba* (construction, medicine), *Piscidia piscipula* (construction), *Brosimum alicastrum* (food, shade), *Pouteria campechiana* (food, latex) and *Manilkara zapota* (food) (Ford, 2011; Ford, 2008). Along with various other species, palms played a crucial role in these forest gardens, promoting various uses from construction to medicine (Ford, 2011). However, whilst ethnobotanical research has provided important insights into how the modern forests of Central America may reflect past management strategies, there is a clear lack of temporal perspective which can be afforded by palaeoecological studies.

The archaeological site of Ceren has been previously dubbed the Pompei of Central America, as the Loma Caldera volcano coated the site in ash around 650 CE (McKee and Sheets, 2003). Despite the destruction caused by the volcano at the time, the preservation of the archaeological site in ash has revealed important insights regarding the diverse use of plants at the site of Ceren. Contents from vessels found in Ceren has revealed that staple crops maize (*Zea mays*), beans (*Phaseolus vulgaris)*, squash (*Cucurbita sp.*) and chilli peppers (*Capsicum annuum*) were found in the vessels (Lentz *et al*., 1996). Along with these staple crops, seeds of cotton (*Gossypium sp.*) and Cacao (*Theobroma cacao*) were found, which are argued to have been used as sources of cooking oil which was extracted from the cottonseed (Lentz *et al*., 1996). Smaller plant remains such as capulin (*Muntingia calabura*) and hackberry (*Celtis sp*.), both which produce sweet berries, were also found (Lentz *et al*., 1996). These findings, plus many others, have provided a temporal context required for ethnobotanists to argue that the ancient Maya diversified their plant use strategies to maximise their use of the forest, in potentially an ecologically sustainable manner (Ford, 2011). Along with the site of Ceren providing the temporal perspective, pollen records provide the opportunity to detect changes in forest composition and can also detect periods of cultivation at relatively high temporal resolution. However, these methods are often discounted by leaders in the ethnobotanical field, due to issues related to pollen production and deposition. Ford (2011; 2008) argues that the domination of insect-pollinated plants in the forests of Central America severely limits the use of pollen as an appropriate proxy for understanding ancient Maya land-use. Whilst these issues are prevalent in tropical environments, pollen can still provide appropriate interpretations regarding ancient Maya land-use.

Table 2.2 List of important plant species associated with the ancient Maya and the palaeoecological interpretations presented in this thesis. Other economic uses of these species are also presented based on ethnobotanical information when available.

Taxon name	**Common name**	**Palaeoecological interpretation**	**Economic uses**	**References**
Zea mays	maize	Cultivation	food	Ford,2008; Leyden, 2002; Pohl *et al*., 2007
Cucurbita sp.	squash	cultivation	food	Piperno and Flannery, 2007; Rushton, Metcalfe and Whitney, 2012
Poaceae	grasses	Disturbance indicator/openness	Potentially used for thatching and clothing	Ford, 2008/2015; Leyden,2002; Curtis *et al.*, 1996
Asteraceae		Disturbance indicator	N.A	Curtis *et al*., 1996; Bhattacharya, Beach and Wahl, 2011
Cecropia spp.		Coloniser tree/secondary forest taxa/openness indicator	Potentially used in agricultural fallow systems	Lentz *et al*., 2015; Islebe *et al*., 1996
Brosimum alicastrum	Maya nut/ breadnut	Primary forests species/economically important taxa	Shade/ fruit used for food	Ford *et al*., 2008/2015.; Meuller *et al*., 2010
Mimosa spp.		shrub/disturbance	N.A	Leirana-Alcoce and Parra-Tabla, 1999; Wahl, Estrada-Belli and Anderson, 2013
Bursera Simaruba	gumbo-limbo	Secondary forest taxa/ early coloniser species	Fruit year-round, wind-resistant species	Ford 2015; Bhattacharya, Beach and Wahl, 2011;
Ficus spp.	Fig trees (*Amate* Maya name for Ficus maxima)	Primary forest	Fruit	Ford, 2015; Rosenmeier *et al*., 2012

Acrostichum aureum	golden leather fern	Mangrove associated fern	N.A	Thomas *et al*., 2016;
Rhizophora mangle	Red mangrove	Mangrove vegetation	N.A	Wooler *et al*., 2016
Sagittaria		Aquatic vegetation		Krause *et al*., 2019
Cyperaceae	Sedges	Dry forest/disturbance/potential shoreline vegetation		Correa-Metrio *et al*., 2011; Bridgewater 2012
Pinus spp.	Pine	Economically important species/potential long wind transportation	Construction	McNeil *et al*., 2012; Rushton, Metcalfe and Whitney, 2012
Arecaceae	palms	Dry forest vegetation/economically important species	Construction/edible fruits	Ford (2008;2012); Rushton, Metcalfe and Whitney,2012
Moraceae/Urticaceae	Mulberry/nettles	Primary dry forest species	Fruit-bearing species present in the family	Gosling *et al*., 2009;Islebe *et al*., 1996
Chenopodiaceae/Amarantaceae		Disturbance species	Potential dyes and flavourings (*Chenopodium ambrosiodes*)	Colunga-GarcíaMarín and Zizumbo-Villarrea ,2004;Leyden *et al*., (1998;2002)
Celtis spp.	hackberries	Early coloniser species/dry forest species	Berries for consumption	Correa-Metrio *et al*., 2011;Lentz *et al*., 1996
Spondias mombin	Hog plum	Forest species from the cashew family	Fruit for consumption	Nigh,2008

2:7:2 Palaeoecological evidence for ancient Maya land-use

Diverse research strategies have attempted to quantify ancient Maya land-use, with some palaeoecological studies combining evidence for crop pollen with changing percentage of economically important species to determine the role these types of taxa played in ancient Maya management of the landscape (McNeil *et al.*, 2010; Rushton, 2012). Others investigate broad changes in pollen taxa alongside cultigen pollen to understand the complex processes involved with ancient Maya land-use (Leyden *et al.*, 2002; Mueller *et al.*, 2010). Currently, palaeoecological records focusing on ancient Maya land-use are focused on the urban capitals of the Maya Highlands and Lowlands (Leyden *et al.*, 2002; McNeil *et al.*, 2002; Walsh *et al.*, 2014). The low special resolution of study sites, regarding sampling density per region and the perceived populations during the ancient Maya period limits inter-site comparability. Further limitations to inter-site comparability are linked to the physical environments where these records are taken. Variations in lake basin size, geochemistry of the lakes and surrounding local vegetation makes comparisons between sites more difficult, due to large variations in how pollen is distributed and deposited at the specific site. Palaeoecological interpretations focus on changing percentages of arboreal and non-arboreal pollen to understand the extent of ancient Maya forest clearance (Figure 2.7), whilst increasing charcoal concentrations associated with periods of cultivation infer the role of fire in managing the landscape. Due to temporal heterogeneity associated with cultural phases of the ancient Maya, this discussion has been split between the northern lowlands, the southern lowlands and the southern highlands. Selection of sites for this discussion required records to have evidence for a human presence on the landscape, thus the El Palmar palaeoecological record (Islebe *et al.*, 2006) that was mentioned in the previous section (between the Quintana Roo and Belizean border) was not included. Numbering following site names refers to the key in Figure 2.7.

From an ecological perspective, numerous vegetation groupings have been associated with a change in the ecological conditions (from forest regrowth to disturbance). One of the major issues with these groupings is the low taxonomic resolutions available regarding pollen identification for certain plant groups. Families such as Arecaceae and Asteraceae represent a wide range of groupings (from trees to shrubs) and therefore can have contrasting interpretations. Table 2.2 identifies the most frequent and discussed pollen types identified in this thesis and the palaeoecological interpretations associated with them.

From a family level, taxa identified as Poaceae (bar *Zea mays*), Asteraceae and Chenopodiaceae/Amaranthaceae are interpreted as openness/disturbance indicators (Table 2.2), along with genus-level identifications of *Cecropia*, *Mimosa* and *Celtis*. These taxa are usually quick colonisers in disturbed environments, whilst the family identified taxa are primarily associated with grasses and weeds. Cyperaceae is a problematic identification due to its prevalence in growing alongside lakeshores and in savannah ecosystems. Determining whether the Cyperaceae concentrations are indicating changing in vegetation around the shoreline or the terrain where the dry forest is located will require further discussion in the context of broader patterns of ecological change. As genus from the family of Moraceae and Urticaceae (*Brosimum spp*., *Maclura spp.* and *Ficus spp.*) are associated with mature forest vegetation, they have been grouped under the family name Moraceae/Urticaceae (Table 2.2).

2:7:2:1 The Northern Lowlands

In the northern Maya Lowlands, the establishment of maize cultivation is recorded throughout sites *ca* 2200-1600 BCE, with the earliest record from Lake Silvituc (5) (Torrescano-Valle and Islebe, 2015) followed by Ria Lagartos (1) (Aragón-Moreno, Islebe and Torrescano-valle, 2012), Lake Tzib (Carrillo-Bastos *et al.*, 2010) (15) and Lake Coba (3) (Leyden, Brenner and Dahlin, 1998; Leyden, 2002) (Figure 2.7). For the remainder of sites in the northern lowlands, evidence for ancient Maya cultivation was not established until the Classic (~300 CE) at Lake Chichancanab and the late Postclassic at Cenote San Jose Chulchaca (Leyden, 2002). Of these records, only Ria Lagartos and Cenotee San Jose used charcoal as a proxy for land-use change in the northern lowlands.

Associated with these periods of cultivation, large declines in forest cover are recorded at numerous sites during the Preclassic with a 60% reduction in arboreal pollen recorded at Lake Coba from 900 BCE (Leyden, 2002) (Figure 2.7). Peaks in charcoal are recorded in Ria Lagartos at *ca* 1500 BCE, associated with the presence of *Zea mays*, indicating the use of fire as a method of land-use in the area (Aragón-Moreno, Islebe and Torrescano-valle, 2012). At Lake Tzib, the presence of maize at *ca* 1500 BCE, increasing Poaceae percentages and increasing trees indicating disturbance (*Cecropia*, *Croton*) has been interpreted to ancient Maya impact on forest vegetation (Carrillo-Bastos *et al*., 2010). Whilst periods of forest clearance continue at Lake Coba, associated with increasing population pressures at the regional capital of Coba (Leyden, 2002; Folan *et al.*, 2009), forest recovery is recorded at Ria Lagartos between 600 BCE – 100 CE. This period of

forest recovery has been interpreted as site abandonment (Aragón-Moreno, Islebe and Torrescano-valle, 2012), potentially indicating population movements towards Coba. At 200 CE Ria Lagartos records a period of forest reduction during a period drought (Aragón-Moreno, 2012), although, the climate is not attributed as the driver due to the continued presence of *Zea mays* in the palaeoecological record (Aragón-Moreno, 2012). Furthermore, peaks in the charcoal record are recorded between 200 BCE - 200 CE providing additional evidence for ancient Maya land-use. The evidence for increasing activities around the Ria Lagartos lagoon potentially shows the importance of the water resource during times of drought, recorded across numerous palaeoclimate investigations (Carrillo-Bastos *et al.*, 2010; Kennett *et al*., 2012; Webster *et al.,* 2006). The Preclassic abandonment period, where numerous sites were abandoned and closely related to a climate drying event, potentially drove inhabitants to the lagoon site as a secure water resource.

The presence of *Zea mays* continues at Ria Lagartos and Lake Coba until *ca* 700-800 CE, where it then disappears from both records (Leyden, 2002; Aragón-Moreno, Islebe and Torrescano-valle, 2012), with Ria Lagartos showing declining fire activity following the disappearance of maize. At Lake Coba, this disappearance of cultivation has been interpreted to represent the abandonment of the Coba settlement during the Terminal Classic (Leyden, 2002). Further west, Lake Chichancanab records a period of cultivation throughout the Classic and Terminal Classic with minimal impact on forest cover associated with these periods of cultivation (Leyden, 2002). Continued periods of cultivation are also recorded at Lake Tzib, throughout the Classic and into the Terminal Classic period, with relatively low impacts on forest abundances recorded (Carrillo-Bastos *et al*., 2010). Following the Terminal Classic, Chichancanab records an increase in forest abundances during the Postclassic interpreted to reflect landscape abandonment (Leyden, 2002). Forest recovery at Ria Lagartos and Lake Coba is also present (Leyden, 2002; Aragón-Moreno, Islebe and Torrescano-valle, 2012). Although during this period of forest regrowth Ria Lagartos shows evidence for increasing fire and Lake Coba shows presence for cultivation once more potentially indicating that the sites were re-occupied during the Postclassic (Leyden, 2002). At *ca* 1250 CE, evidence for maize becomes prevalent at Cenote San Jose Chulchaca indicating an increasing use of the landscape during the Postclassic (Leyden, 2002). The charcoal record at Cenote San Jose shows increasing activity at 2800 BCE, 370 BCE and between 570-1260 CE, with the latter the only episode supported with evidence for cultivation. This may indicate that the cenote was used as a water resource, strictly, as the fire episodes managed the landscape to improve access to the resource and the final peak of charcoal associated with *Zea mays.* At Lake Tzib

cultivation continues into the Postclassic (Carrillo-Bastos *et al*., 2010), whilst Lake Silvituc does not record episodes of ancient Maya land-use until the later parts of the Postclassic (~1500 CE) with *Zea mays* presence and increasing in non-arboreal pollen the indicators (Torrescano-Valle and Islebe, 2015).

2:7:2:2 The Southern Lowlands

In Peten Lake District, Guatemala, cultivation of *Zea mays* was established between *ca* 2600-1300 BCE. By 2600 BCE, cultivation was present at Lago Peurto Arturo (8) (Wahl *et al.*, 2006), Lago Paixban by *ca* 1200 BCE (6) (Wahl *et al.*, 2016) and then Lake Salpeten by 500 BCE (9) (Leyden, 1987, 2002) (Figure 2.7). Whilst the establishment of maize at Lago Paixban occurred later than Peurto Arturo, palaeofire records indicate increased burning between 3000-2500 BCE, interpreted as ancient Maya activities (Anderson and Wahl, 2016). These activities are likely the result of *milpa* agriculture, a form of land-use that incorporates the use of fire to clear the landscape and associated field rotation to allow for periods of fallow growth, whilst nearby landscapes are used for agriculture (Daniels, Painter and Southworth, 2008; Ford, 2008; Hartter *et al.*, 2008; Nigh and Diemont, 2013; Lentz *et al.*, 2014). Palaeoecological records have provided important insights into the understanding of the use of fire for agriculture, with the frequency of fire events appearing synchronously with the appearance of cultigen pollen (Rosenmeier *et al.*, 2002; Walsh and Prufer, 2014; Anderson and Wahl, 2016). Increasing quantitative analysis techniques of charcoal data have improved the interpretation of these fire events, with advances made in peak detection, peak frequency and signal detection completed through numerical statistics (Higuera, 2009; Higuera *et al.*, 2010; Kelly *et al.*, 2011; Remy *et al.*, 2018)

Continuing in the lake district, at Lake Peten Itza (7) (Figure 2.7), the earliest evidence for ancient Maya land-use is not established from the presence of cultigen pollen, but rather geochemical evidence indicating increasing erosion driven by forest removal at *ca* 800 BCE (Curtis *et al.*, 1998). Fire evidence also indicates a peak in activity during the later parts of the Preclassic *ca* 1700 BCE (Schüpbach *et al.*, 2015). The discrepancies between clear evidence for ancient Maya disturbance (fire, soil erosion, declining forest pollen abundances) and the lack of evidence for maize cultivation can potentially be explained by the sizes of the respective lakes. *Zea mays* is a relatively large pollen grain and therefore it is transported short distances from the parent plant (Jarosz *et al.*, 2003; Lane, Cummings and Clark, 2010). Lake Peten Itza is the largest of all the lakes in the Peten Lake district (~100km^2) and therefore would have a higher unlikelihood for capturing a local maize signal, with these principles used to explain the lack of evidence for cultivation in Lake Peten Itza and Lago Paixban (~2km^2) (Schüpbach *et al.*, 2015; Wahl *et al.*, 2016). The lakes in Peten, represent an important lesson for interpreting palaeoecological results, as

catchment characteristics need to be incorporated into the understanding of ancient Maya land-use. Following the period of intensified land-use throughout the Peten Lake district, the Classic period sees continued activities around many of the lakes (Leyden, 1987; Curtis *et al.*, 1998; Wahl *et al.*, 2016), bar Lake Salpeten which shows evidence for forest recovery (Leyden, 1987, 2002). This period of forest recovery is reflected later in the records at Peten Itza (1000 CE) and Puerto Arturo (800 CE), interpreted as site abandonment associated with the Terminal Classic and the transition into the Postclassic (Curtis *et al.*, 1998; Wahl *et al.*, 2006). At Lago Paixban, forest reductions are most extensively recorded during the Postclassic period, with a period of forest recovery associated with Spanish conquest *ca* 1600 CE (Wahl *et al.*, 2016) (Figure 2.7).

In Belize, the earliest evidence for ancient Maya use of *Zea mays* has been found in the wetland ecosystems of Cobweb swamp by 3000 BCE (Pohl *et al.*, 1996). Wetland ecosystems have provided numerous lines of evidence for ancient Maya land-use, away from traditional palaeoecological records from lake sediments (Dunning *et al.*, 2002; Beach *et al.*, 2006, 2015; Beach, Luzzadder-Beach, Dunning, *et al.*, 2009; Luzzadder-Beach *et al.*, 2011). These land-use strategies involved the manipulation of wetland ecosystems, to actively cultivate the landscape for usual staple crops of maize, manihot, squash and beans, with soil conservation prioritised through terracing infrastructure (Kunen, 2001; Hightower, Butterfield and Weishampel, 2014; Lentz *et al.*, 2014; Beach *et al.*, 2015). Wetland ecosystems saw high levels of use during the Preclassic and Classic periods, with eventual infillings interpreted to reflect drought-induced abandonment (Beach *et al.*, 2009). The perspective of using different ecosystems for land-use are also evident in coastal regions such as Ambergris Caye. It has been previously described the evidence for marine-based subsistence on the island of Ambergris Caye, with the understanding of crop subsistence limited to macro-fossil evidence from Marco Gonzalez (Graham *et al.*, 2017). Due to the dominance of mangrove vegetation at the Marco Gonzalez site, local growth of maize would have been challenging. Shell midden has been found extensively throughout the Marco Gonzalez site, showing the vast consumption of these marine resources (Figure 2.8). Secondly the presence of highly organic soils, with large quantities of charcoal and human deposits termed “Maya dark earths” an anthropogenic soil formation (Graham *et al.*, 2017). If these soils were deemed to be anthropogenic, then it would indicate that the ancient Maya attempted to practice some degree of land-use for in a mangrove dominated ecosystem. Further research is needed to confirm the presence of these dark-earths and to understand the regional variations of land-

use on the island of Ambergris Caye, to determine if local cultivation was possible and obtainable for communities present in Marco Gonzalez.

From a palaeoecological perspective, evidence for ancient Maya land-use in Belize is provided by New River Lagoon (10) (Rushton, Metcalfe and Whitney, 2012; 2020) and Agua Caliente (11) (Walsh, 2014) (Figure 2.7) with both records showing a strong association between increasing fire activity and methods of land-use. From a subsistence perspective, New River Lagoon (10) shows strong synchronicity between *Zea mays* cultivation and peaks in fire activity at 1200 BCE, with the first appearance of maize by *ca* 1500 BCE (Rushton, Metcalfe and Whitney, 2012). Shortly following this period of cultivation, between ~1150-800 BCE, arboreal pollen concentrations increase, evidence for maize disappears and charcoal concentrations drop. At Agua Caliente, the appearance of *Zea mays* during the Late Preclassic (600 BCE- 200 CE) is associated with the largest period of fire activity in the record, interpreted to reflect land-use (Walsh and Prufer, 2014). The Agua Caliente record does indicate a drop off in fire activity, following the major peak at 600 BCE, interpreted to reflect that fire was primarily used for initial landscape clearance for agriculture (Walsh and Prufer, 2014). The continued occupation of New River Lagoon throughout the Classic period and into the Terminal Classic is seen through the continued presence of *Zea mays* and increasing charcoal concentrations at 600 CE (Rushton, Metcalfe and Whitney, 2012)

The record from New River Lagoon informs how the ancient Maya used managed forest resources at the archaeological site of Lamanai (Rushton, Metcalfe and Whitney, 2012). This research was the first attempt to use *Pinus* concentrations as a proxy for construction, with the archaeological evidence indicating its use in buildings (Pendergast, 1982; Rushton, Metcalfe and Whitney, 2012). The use of economically important species has been extensively described from an ethnobotanist perspective, with the record from Lamanai attempting to use empirical data to support notions of ecological management of the ancient Maya (Rushton, Metcalfe and Whitney, 2012). The record also strongly shows a link between increasing fire activity and the use of pine for fuel, with peaks in the record synchronous with the lowest abundances of pine recorded (Rushton, Metcalfe and Whitney, 2012). The New River Lagoon interpretations provide a crucial step in understanding ancient Maya land-use from a resource perspective, highlighting the values of palaeoecological proxies in interpreting patterns of change associated with ecological management.

2:7:2:3 The Southern Highlands

In Honduras, Petapilla pond (12) shows evidence for *Zea mays* cultivation by 900 BCE (McNeil *et al*., 2010) (Figure 2.7), although this was the maximum stratigraphic age of the shore core and therefore cannot establish if activities existed earlier. In El Salvador, Laguna Verde (13) shows similar evidence for cultivation by 2500 BCE (Dull, 2004), whilst interpretations from Laguna Cuzcachapa (14) suggests high-density maize agriculture existed *ca* 1700 BCE (Dull, 2007) (Figure 2.7). The interpretations for high-density maize agriculture is based on the findings of 20 *Zea mays* pollen grains along a single horizon (Dull, 2007), although the small catchment ($0.1km^2$) could simply indicate that the maize plants were grown adjacent to the water body.

Associated with periods of cultivation, intensified forest clearance is recorded at Pepidilla pond (Honduras), Laguna Verde and Laguna Cuzcachapa (both El Salvador) (Dull, 2004, 2007; McNeil *et al.*, 2010). Declines in cloud forest taxa at Laguna Verde and forest taxa at Laguna Cuzcachapa are attributed to ancient Maya forest clearance during the Preclassic (Dull, 2004, 2007). At Petapilla pond Preclassic forest clearance occurs associated with cultivation between 900-790 BCE, with weedy taxa contributing to almost 90% of the total pollen count (McNeil *et al.*, 2010). Similarly, to the discussion from New River Lagoon, the palaeoecological record from Petapilla pond indicates some degree of ancient Maya resource management, with palms actively maintained by the inhabitants (McNeil *et al.*, 2010). These findings provide additional complexity regarding the understanding of ancient Maya forest management, which can be improved by using palaeoecological records to determine key changes in abundances of economically important taxa. Fire activity is present at all sites during the Preclassic, associated with the cultivation patterns previously described (Dull, 2004, 2007; McNeil *et al.*, 2010).

Regarding the scale and intensity of Maya land-use in the southern highlands during the Classic transition, the Tierra Blanca Joven (TBJ) eruption had a significant impact on land-use in sites in El Salvador, with Laguna Verde showing a halting of Maya land-use at *ca* 400 CE and declining activities at Laguna Cuzcachapa by 430 CE (Dull, 2004, 2007). Activities never restarted at Laguna Verde following its abandonment but did resume at Laguna Cuzcachapa again between 600-950 CE, indicated by increases in maize and weedy pollen (Poaceae and Asteraceae) along with increasing fire activity (Dull, 2004, 2007). Evidence from Petapilla pond indicates reforestation following site abandonment

between *ca* 780-980 CE. Ancient Maya presence then decreases at Laguna Cuzcachapa during the Postclassic (*ca* 1300 CE).

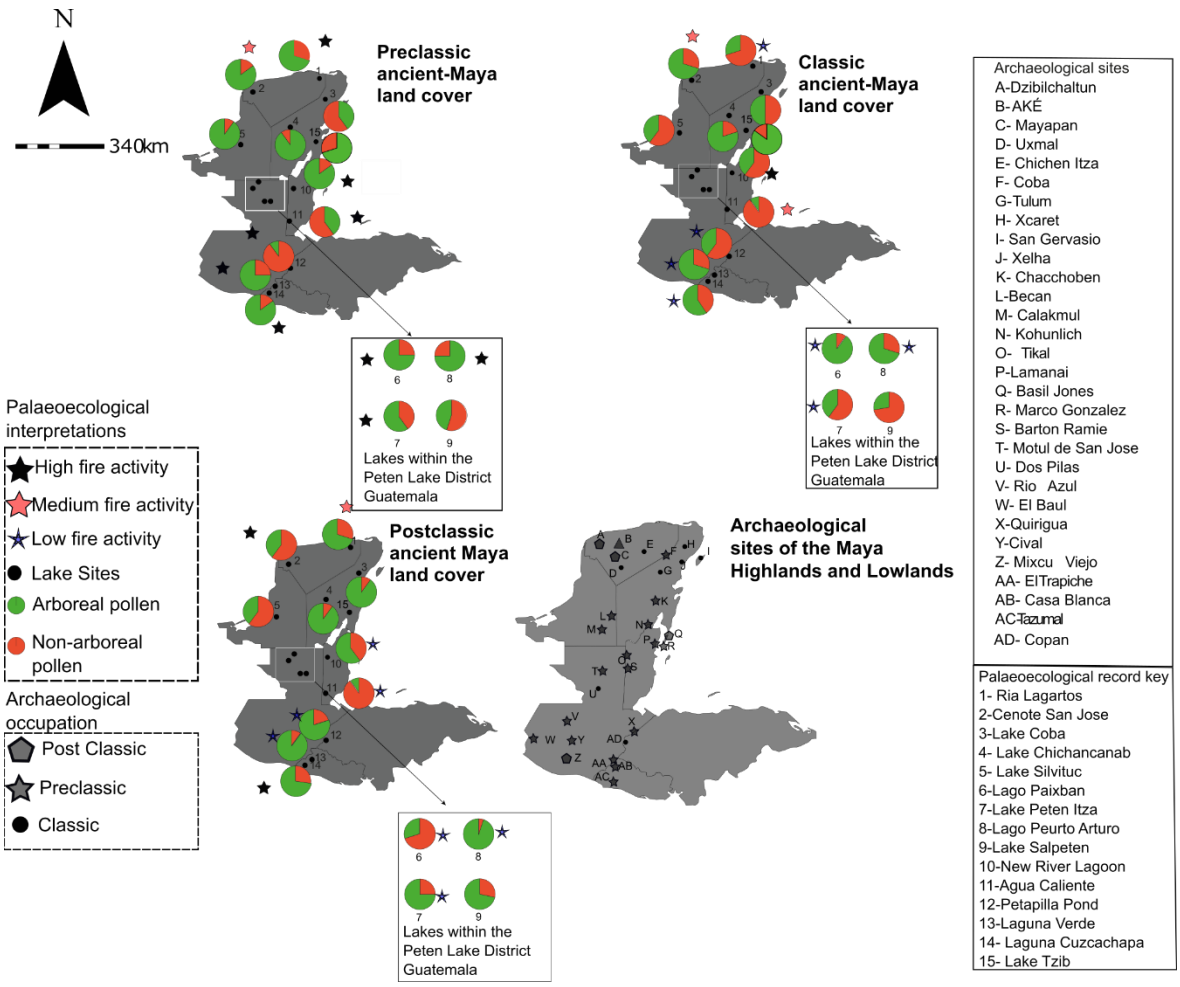

Figure 2.7 Regional heterogeneity of patterns of forest cover change recorded in palaeoecological records from Central America. Pie charts represent the relationship between arboreal and non-arboreal pollen across the key Maya periods. Black bars represent the magnitude of fire activity ranging from high-low. References for palaeoecological data include;(1)Ria Lagartos(Aragón-Moreno, Islebe and Torrescano-valle, 2012)*;(2) Cenotee San Jose (3)Lake Coba and (4) Lake Chichancanab (Leyden, 2002); (5)Lake Silvituc* (Torrescano-Valle and Islebe, 2015)*;(6)Lago Paixban* (Anderson and Wahl, 2016; Wahl *et al*., 2016)*; (7) Lake Peten Itza* (Islebe *et al*., 1996; Schüpbach *et al.*, 2015)*; (8)Lago Peurto Arturo* (Wahl, Byrne and Anderson, 2014)*; (9)Lake Salpeten* (Leyden, 2002; Rosenmeier *et al.*, 2002)*;(10)New River Lagoon* (Rushton, Metcalfe and Whitney, 2012)*;(11) Agua Caliente* (Walsh and Prufer, 2014)*;(12) Pepidilla Pond* (McNeil, Cameron L., Burney and Burney, 2010)*; (13) Laguna Verde (Dull, 2004); (14) Laguna Cuzcachapa (Dull, 2007). (15) Lake Tzib (Carrillo-Bastos et al., 2010)*

Figure 2.8 Example of the shell midden deposited around the mangrove site of Marco Gonzalez, Ambergris Caye. Highlighting the use of marine subsistence by ancient Maya communities on the island (July 2017)

Chapter 3 Materials and Methods

3:1 Overview

This chapter outlines the details for the methodological approach used in the collection and analysis of the samples extracted from Ambergris Caye, Laguna Esmeralda, Lake Chichancanab. A description of the physical and archaeological setting of both major study sites (Laguna Esmeralda, Ambergris Caye are discussed). Here a multiple proxy palaeoecological approach has been conducted to determine ancient Maya land-use in seasonally dry tropical forest ecosystems in the Maya Lowlands. Fossil pollen and macroscopic charcoal were analysed to establish patterns of ancient Maya land-use. Numerical analysis of the fossil data was completed to determine the significant changes in the records. To determine if the raw charcoal data represent signals in the record, and thus localised fire events, the raw charcoal data was analysed through the CHARanalysis protocol. An analysis of surface sediments from Lake Chichancanab and Laguna Esmeralda was completed to understand how the respective lakes represent modern forest cover. Environmental data was extracted to complete an ordination analysis (PCA, RDA) to complement the surface sample pollen data. Previously published pollen datasets were replotted and reinterpreted to link the modern surface data to the palaeoecological record.

3:2 Yucatan Peninsula study sites

The scope of this research investigates the land-use strategies of the ancient Maya within the Yucatan Peninsula. Dominated by seasonally dry tropical forest ecosystems, along with limited access to surface water (such as lakes and rivers) this research examines two sites within Quintana Roo. The first site is a lake from the Quintana Roo region known as Laguna Esmeralda, located adjacent to the well-researched Lake Chichancanab (Hodell, Curtis and Brenner, 1995; Hodell *et al.*, 2005; Evans *et al.*, 2018). The second site is an island, Ambergris Caye, located off the eastern coast of mainland Belize. Vegetation richness is low, potentially linked to the geological past of the region (Fernández-Concha and Tapia-Munoz, 2010; Torrescano-Valle and Folan, 2015). Despite this low vegetation richness, high percentages of endemic trees are recorded throughout the Yucatan Peninsula with a total of 72 species recorded (Torrescano-Valle and Folan, 2015). Floristic inventories show that Euphorbiaceae, Fabaceae and Orchidaceae contain the highest number of species (Torrescano-Valle and Folan, 2015). Ecosystem diversity and

distribution is primarily driven by regional-scale variations in precipitation, topographic and soil types. Regional differences in precipitation show the formation of seasonally dry tropical forests (with and without cacti) in low precipitation areas (<800m), medium canopy forest and low canopy deciduous forest (1000-1200mm), high and medium semi-evergreen forest/flooded semi-evergreen forests (1100-1300mm) and high evergreen forests (1500-2000mm) (Sanchez and Isleve, 2002; White and Hood, 2004; Ramírez-Barahona *et al.*, 2009; Torrescano-Valle and Folan, 2015). Other dominant ecosystem types in the Yucatan Peninsula include Poaceae and Cyperaceae dominant savannahs (Durán-García, Méndez-González and Larqué-Saavedra, 2016), pine forests in Belize and Guatemala (Laughlin, 2002; Holder, 2004), palm groves found near-surface water and mangroves dominating coastal areas (Zaldívar-Jiménez *et al*., 2010).

3:3 Ambergris Caye

3:3:1 Physical setting

The island of Ambergris Caye (Figure 3.1) is a 40 km long and less than 1 km wide island located off the eastern coast of Belize. The Pleistocene reef limestone, the bedrock of the Caye, is constructed from the Belizean Barrier Reef (Graham *et al.*, 2017). Extensive swampy and mangrove vegetation exists throughout the entirety of the island with parts of dry forest located in the north (Meerman, 2004). Topography shows clear variations between the windward and leeward side of the island, with the windward ranging between 4-7 meters above sea level, with a maximum elevation approximately 12m (Floodmap, 2020). The windward side is mainly below sea level (approximately -1 meters below sea level), with the coastal margin between 3-4 meters above sea level. Average temperature ranges between 27- 32°C with the coldest month occurring in December and the warmest months between April-August. The same large-scale processes as the Maya lowlands control precipitation, with the distinct dry season occurring between January - April and the wet season between May-December. Minimum average precipitation is recorded at 37mm (March) whilst the highest average occurs in October (245mm). The number of rainy days between the wet and dry season is also distinct with the dry season receiving between 4-11 rainy days and the wet season receiving 12-16 days. Average daylight hours are 11-12 hrs all year. The coring location was selected close to the documented house mounds of the archaeological site known as Basil Jones (Guderjan, 1995). A sinkhole, which cannot be defined as an aguada or a cenote due to unknown hydrological features, was selected as a local field guide suggested it was wet all year round. Local vegetation

composition has been provided by satellite imagery composed by Meerman (2004) defined as a lowland semi-deciduous broadleaf forest, with identification of dry forest confirmed during fieldwork. Vegetation composition suggests the forest contains species such as *Bursera simaruba, Gymnopodium floribundum* and *Metopium brownei* whilst legume type *Acacia* sp. also frequent (Meerman, 2004).

3:3:2 Archaeological context

The first evidence for occupation on Ambergris Caye is thought to have occurred during the Late Preclassic (*ca* 300 BCE), with the southern archaeological site of Marco Gonzalez and the northern site of Chac Balam the only available evidence for this period of occupation (Guderjan, 1995; Graham *et al.*, 2017). Whilst no radiocarbon dating is available to support this Preclassic occupation, relative stratigraphy has been used to date the early construction periods at Marco Gonzalez and suggest that the Late Preclassic is the minimum occupation phase (Graham *et al.*, 2017). The chronology of Chac Balam, as a Preclassic site, is limited to the finding of a single sherd, which is argued to have been deposited during the Late Pre Classic (Driver, 1991; Guderjan, 1995). However, despite the lack of evidence, the proximity of Chac Balam to an important waterway (The Bacalar Chico) highlights how the site may have been originally used. The Bacalar Chico is a navigable passage of water that separates the north of the island from the mainland Yucatan Peninsula, with architectural similarities between the north of the island and the mainland identifying some degree of connection between the two areas (Guderjan, 1995). It remains possible that early canoers accessed Ambergris Caye through this point and occupied the northern part of the island by the Pre-Classic.

By the Late Classic (*ca* 600 CE), numerous settlements emerge around the island, with sites appearing on the windward side, suggesting as a predominately fishing based lifestyle (Guderjan, 1995). Whilst this is seen as a period of growth, populations densities are low compared to mainland centres (in the hundreds for population estimates) (Guderjan, 1995). Chronological controls for the occupation of these sites are driven by architectural similarities seen on mainland sites, suggesting the growth of trade networks with the mainland. Evidence of high proportions of exotic goods, mainly in the form of obsidian, and circular architectural styles have suggested that the sites of Chac Balam and San Juan were trade ports, with potential Yucatan/Belizean influence (Guderjan *et al.*, 1989; Guderjan, 1995). Marco Gonzalez shows evidence for salt working and trading with the mainland Belizean site of Lamanai (Graham *et al.*, 2017). The Terminal Classic - Early

Postclassic (750-1200 C.E) shows the abandonment of leeward settlements and inward migration to the interior site of Basil Jones (Postclassic occupation) (Guderjan, 1995). Marco Gonzalez shows evidence for increased construction during the early parts of the Postclassic, but then rising sea levels result in mangrove encroachment and the abandonment of Marco Gonzalez (Dunn and Mazzullo, 1993; Graham *et al.*, 2017). The ancient Maya of Marco Gonzalez most likely migrated from the site and occupied the other coastal site of San Pedro during the Late Postclassic (*ca* 1200 C.E) (Graham *et al.*, 2017). Information on the settlement organisation at San Pedro is limited due to the original site being covered by modern buildings (Stemp, 2016). The site of San Pedro was still active in the trading of obsidian, with high degrees of green obsidian sourced from Guatemala recovered (Stemp, 2016).

The site of Basil Jones (N 18.09/W -87.89), the focus of this research, covers a $3km^2$ area consisting of beaches, dry forest and mangrove vegetation. The archaeological site has the Maya name of Bercellon, differentiating the archaeological site from the wider Basil Jones area, but for this chapter, it will refer to the entire site as Basil Jones. Basil Jones is located within the seasonally dry tropical forest ecosystem and located close to the aforementioned sinkhole. The site is likely named after the owner of a plantation in the northern part of the island by the same name in the 18^{th} century (Godfrey, 1999).

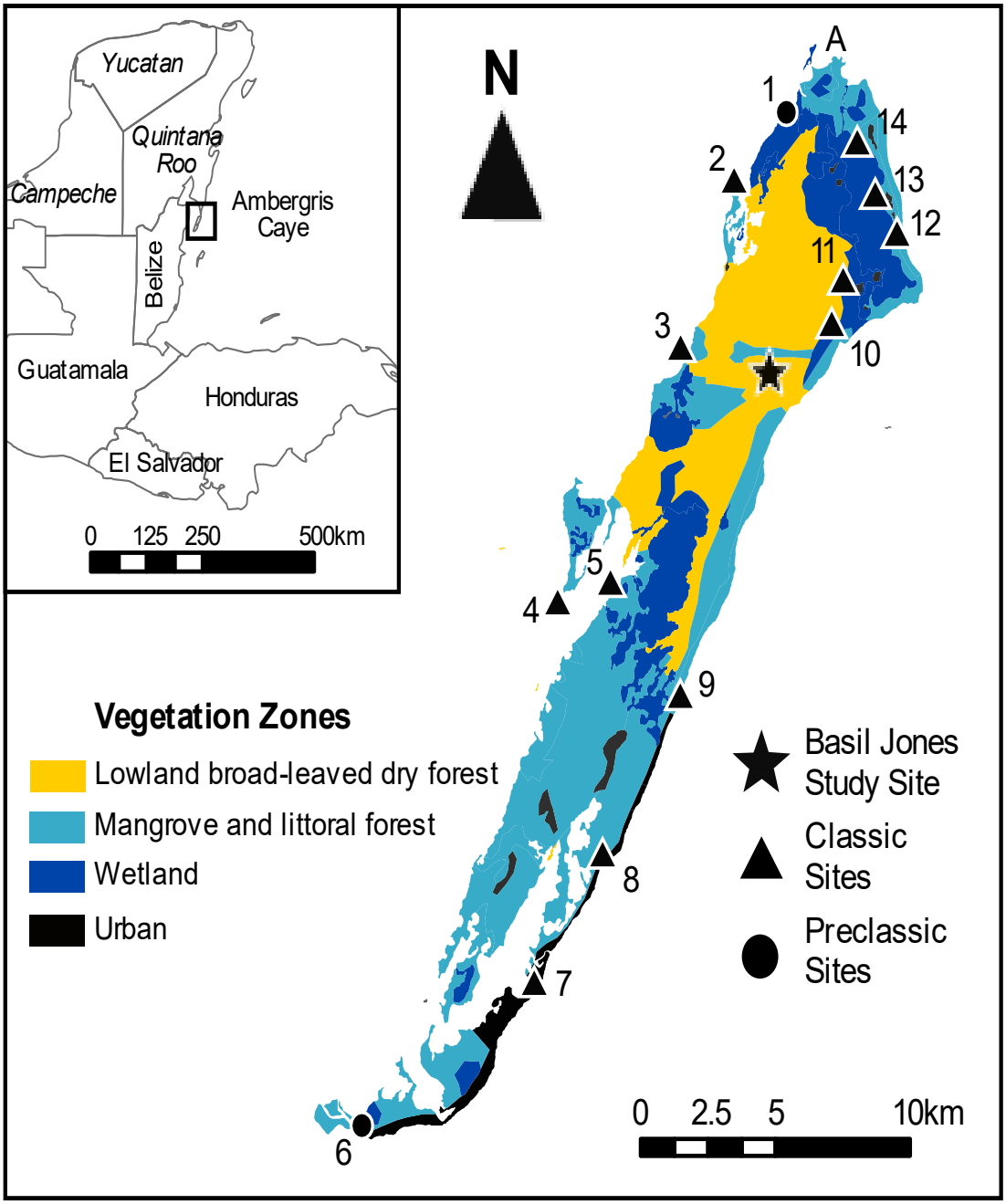

Figure 3.1 Map of Ambergris Caye, Belize. Vegetation zones are taken from Meerman (2004). Archaeological sites are from Guderjan (1995) and Graham et al. (2017). 1. Chac Balam, 2. San Juan, 3. Santa Cruz, 4. Yalamha, 5. Laguna de Cayo Francesca, 6. Marco Gonzalez, 7. San Pedro, 8. Tres Cocos, 9. Los Renegados, 10. Robles Point, 11. Burning Water, 12. Franco, 13. Valencia, 14. Ek Luum, A. Boca Bacalar Chico canal,

3:4 Laguna Esmeralda

3:4:1 Physical setting

Laguna Esmeralda (N 19.814/W -88.728) is a lake located in the dry forest ecosystem of the northern Yucatan Peninsula (Figure 3.2). Generally, in the northern Yucatan, species such as *Bursera simaruba, Caesalpinia gaumeri* and *Gymnopodium floribundum* are found, whilst variations in assemblages differ along the east-west transect studied (White and Hood, 2004). Species such as *Brosimum alicastrum* and *Croton lundellii* are particularly prominent on sites with ancient Maya housing ruins, potentially linked to the soil properties associated with these sites (White and Hood, 2004). The Yucatan state is actively managed through *milpa* agriculture resulting in short forest recovery cycles, as the Quintana Roo and Campeche state show higher percentages of forest cover on a regional scale (Urquiza-Haas, Dolman and Peres, 2007). Located in the Quintana Roo region, Laguna Esmeralda contributed a major part of this research, whilst a series of surface samples were examined from the adjacent Lake Chichancanab. It has been hypothesised that these lakes were once connected during times of high-water (Hodell *et al.*, 2005).

3:4:2 Archaeological context

There is currently no documented evidence for settlements in the proximity of Laguna Esmeralda or Lake Chichancanab, but mounds, likely to be small occupational sites, require further investigations to verify this. With no available local insights, a wider regional archaeological perspective of the Quintana Roo district will be provided. Larger temple sites such as Coba and Chichen Itza, located in the eastern region of Quintana Roo, have been already been discussed from this perspective and will thus not be repeated here.

In the south-central Quintana Roo region, sites such as Margarita and Lagartera show occupation as early as the Middle-Preclassic Period (*ca* 500 BCE) (Villamil, 2009; Villamil and Sherman, 2017). Towards the end of the Preclassic, Margarita was established as a minor centre as other sites such as Dzibanche began constructing monuments (Nalda, 2005; Nalda and Balanzario, 2014). Towards the transition into the Classic (*ca* 300 CE), populations grew in the region as Lagartera and Margarita continued to develop (Villamil and Sherman, 2017). In the Terminal Classic (*ca* 900 CE), sites experienced various phases of growth and decline, with many abandoned. In response to these abandonments,

numerous previously smaller centres grew in population, such as Kohunlich that peaked during the Terminal Classic (Nalda, 2005; Nalda and Balanzario, 2014; Villamil and Sherman, 2017). The previous large centres of Lagartera and Margarita were abandoned during this period, which may explain the establishment of smaller centres throughout the region. In the northern Yucatan, the Maya region of Cochuah has been under-represented in ancient Maya research, due to the influence of the Caste wars (1847-1901 CE) during the time of emergent Mayanist research (Shaw, 2000; Normark, 2006; Sanchez, 2015). Major centres of Yo'okop and Ichmul are located approximately 20km away from the Esmeralda and Chichancanab watershed so do not represent ''nearby'' archaeological settlements. Yo'okop is hypothesised to have been occupied during the Preclassic (*ca* 600-300 BCE) with smaller settlements throughout the region potentially connected through causeways to these major centres, but archaeological interpretations are limited (Normark, 2006). During the Preclassic, activity seems to increase as the transition to the Classic records a hiatus in construction across these settlements (Sanchez, 2015; Shaw, 2015). During the Terminal Classic, populations show similarities to the southern Quintana Roo region with increasing and decreasing population dynamics occurring on site-specific locations (Normark, 2006). The Postclassic shows increasing construction at Yo'okop with populations moving back following site abandonment during the Terminal Classic. This could also indicate that the site was continuously occupied, but in smaller densities (Shaw, 1998, 2000; Normark, 2006).

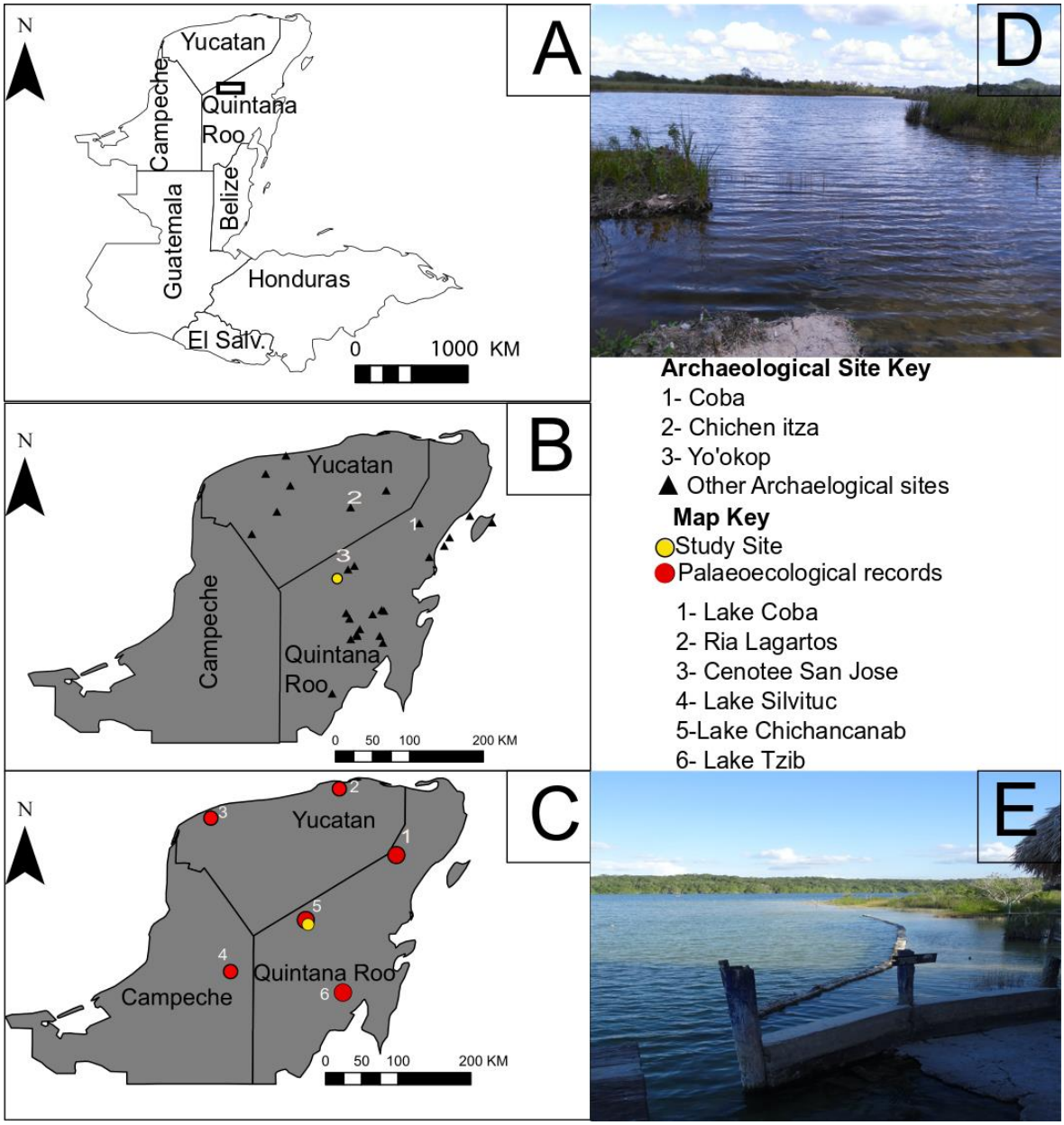

Figure 3.2 Map highlighting the location of the study sites within (A) Central American Continent. (B) Archaeological context with sites 1-2 important political capitals during the ancient Maya era and Yo'okop the closest archaeological site to the Laguna Esmeralda watershed. (C) Map highlighting the palaeoenvironmental investigations completed in the region. (1) Lake Coba (Leyden, 2002);(2) Ria Lagartos (Aragón-Moreno, Islebe and Torrescano-valle, 2012)*; (3) Cenotee San Jose (Leyden, 2002);(4) Lake Silvituc* (Torrescano-Valle and Islebe, 2015)*; (5) Lake Chichancanab (Leyden, 2002). (D) Digital photograph of Laguna Esmeralda with coring location in the distance. (E) Digital photograph of Lake Chichancanab both obtained in January 2020.*

3:5 Core recovery and surface sample collection:

3:5:1 Basil Jones

In 2016, a 350cm sediment core was extracted from a sinkhole located at Basil Jones (Ambergris Caye) using a Russian corer (Wright, Mann and Glaser, 1984). The core was extracted from the centre of the small sinkhole, with an overlap taken between 200-350cm to ensure complete core recovery. Core was composed of mainly woody brown peat (0-50cm, 200-300cm) and woody brown/black peat (50-125cm, 150-200cm, 300-345cm). One transition to reddish woody peat is recorded between 137-150cm, with one final clay layer recorded at the bottom of the core (345-350cm) (Figure 3.3).

3:5:2 Laguna Esmeralda

Laguna Esmeralda was cored over numerous field seasons (2014-2016) using a Livingstone-type corer (Livingstone, 1955; Wright, 1967). Using a coring platform, eight cores were extracted in parallel sequence recovering a maximum of 380cm of continuous sediment (Figure 3.3). For this research samples from all eight cores were extracted for pollen, with the upper four cores (ES-16-01-I, ES-16-01-II, ES-16-02-I, ES-16-02-II) analysed for charcoal and the remaining bottom two cores (ESM-14-3, ESM-14-4) analysed for charcoal by colleagues in Nottingham University.

Figure 3.3 Lithology diagram for the Basil Jones core.

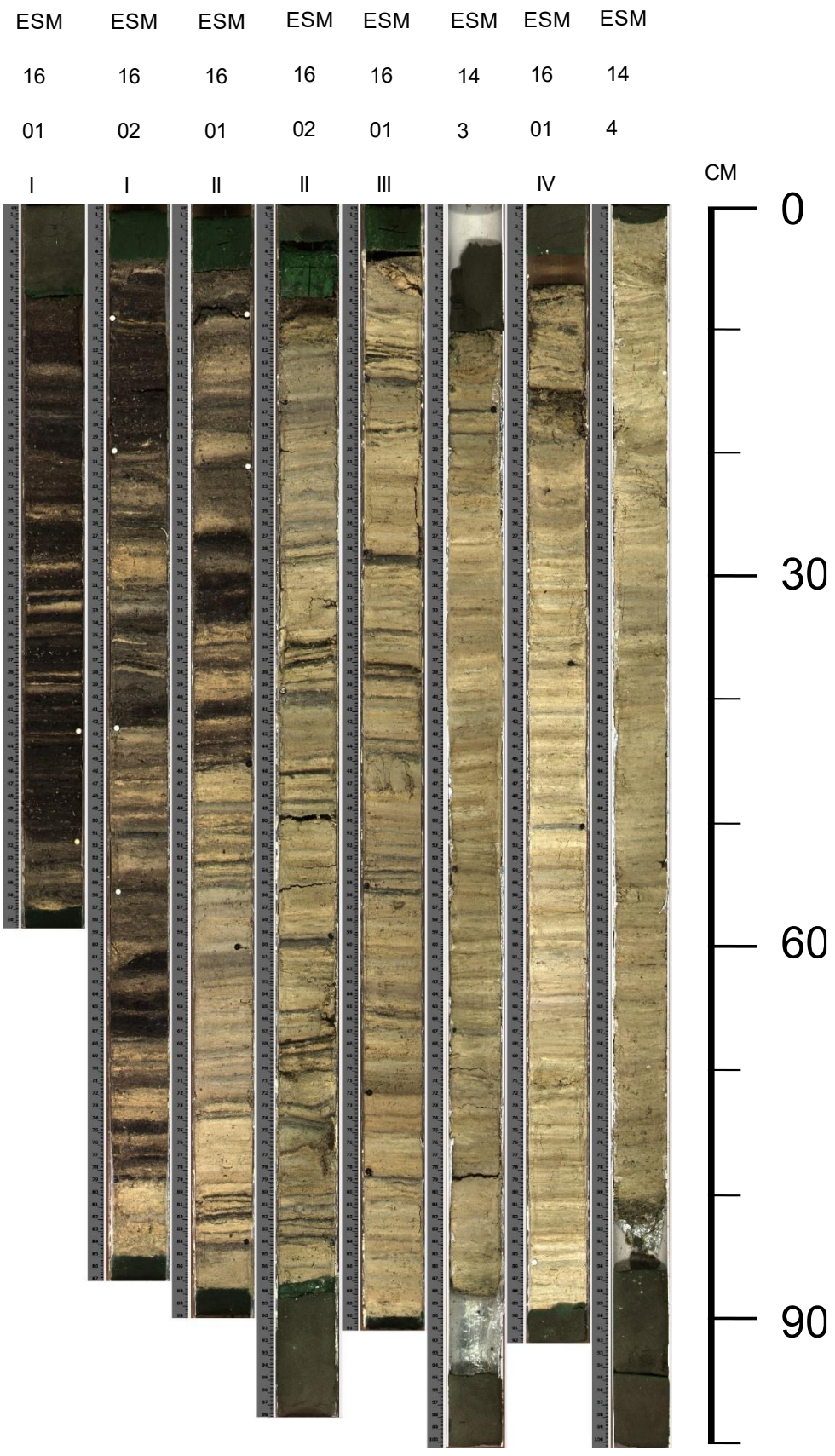

Figure 3.4 Lithological images from the Laguna Esmeralda core. From left to right the core (master depth) is as follows: ESM-16-01-I (2-46cm), ESM-16-02-I(46.5-106.5cm), ESM-16-01-II(107-145cm),ESM-16-02-II((147-193cm), ESM-16-01-III(195-213cm), ESM-14-3 (214.5-309.5cm), ES-16-01-IV (291-309.5cm) and ESM-14-4 (305.5-391.5cm).

3:5:3 Surface Sample Collection

In January of 2019, surface samples were taken along transects of Lake Chichancanab and Laguna Esmeralda. Using transparent tubes, to ensure the water-sediment interface was captured, eight surface samples were extracted from Esmeralda and six from Chichancanab (Figure 3.4). Water depth, temperature and pH were also recorded in the field using probes (Table 3.1)

*Table 3.1 Surface samples extracted from Lake Chichancanab and Laguna Esmeralda *samples not analysed due to poor pollen preservation.*

Site	**Sample number**	**Latitude / Longitude**	**Water depth (m)**	**Temperature (°C)**	**PH**
Esmeralda	1	19.78356, -88.73467	0.7	26.4	7.83
Esmeralda	2	19.78311, -88.73689	0.4	26.1	7.92
Esmeralda	3	19.78324, -88.73689	1.0	26.7	7.86
Esmeralda	4	19.78337, -88.73692	1.4	26.5	7.88
Esmeralda	5	19.78352, -88.73692	2.5	26.6	7.93
Esmeralda	6	19.783618, -88.736922	1.5	26.5	7.88
Esmeralda	7*	19.782824, -88.739413	1.3	26.3	8.01
Esmeralda	8	19.78356, -88.73467	1.1	26.4	7.98
Chichancanab	1	19.87734, -88.76946	1.6	26.3	7.89
Chichancanab	2	19.87747, -88.768879	5.4	25.5	7.94
Chichancanab	3*	19.877635, -88.768142	7.3	25.2	7.92
Chichancanab	4	19.877857, -88.767034	10.8	24.6	7.92
Chichancanab	5	19.878341, -88.766576	11.1	24.6	7.66
Chichancanab	6	19.878261, -88.765851	11.7	NA	NA

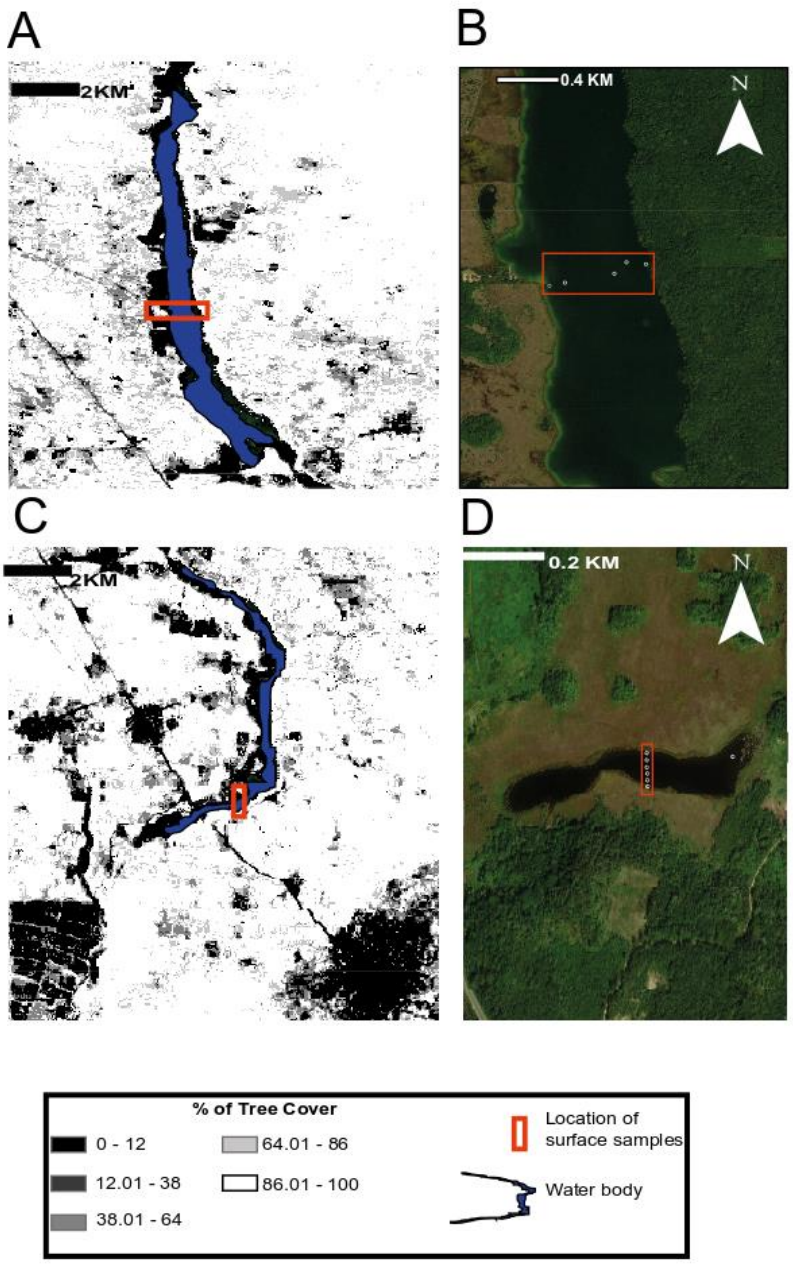

Figure 3.5 Location of surface samples taking along the Lake Chichancanab and Laguna Esmeralda lakes. Samples not included in the analysis were removed from the transect. (A) Percentage forest cover map of Lake Chichancanab with aerial photograph (B) showing surface sample transect. (C)Percentage forest cover map of Laguna Esmeralda with aerial (D) map showing the location of surface samples Red boxes show the position of the respective transects

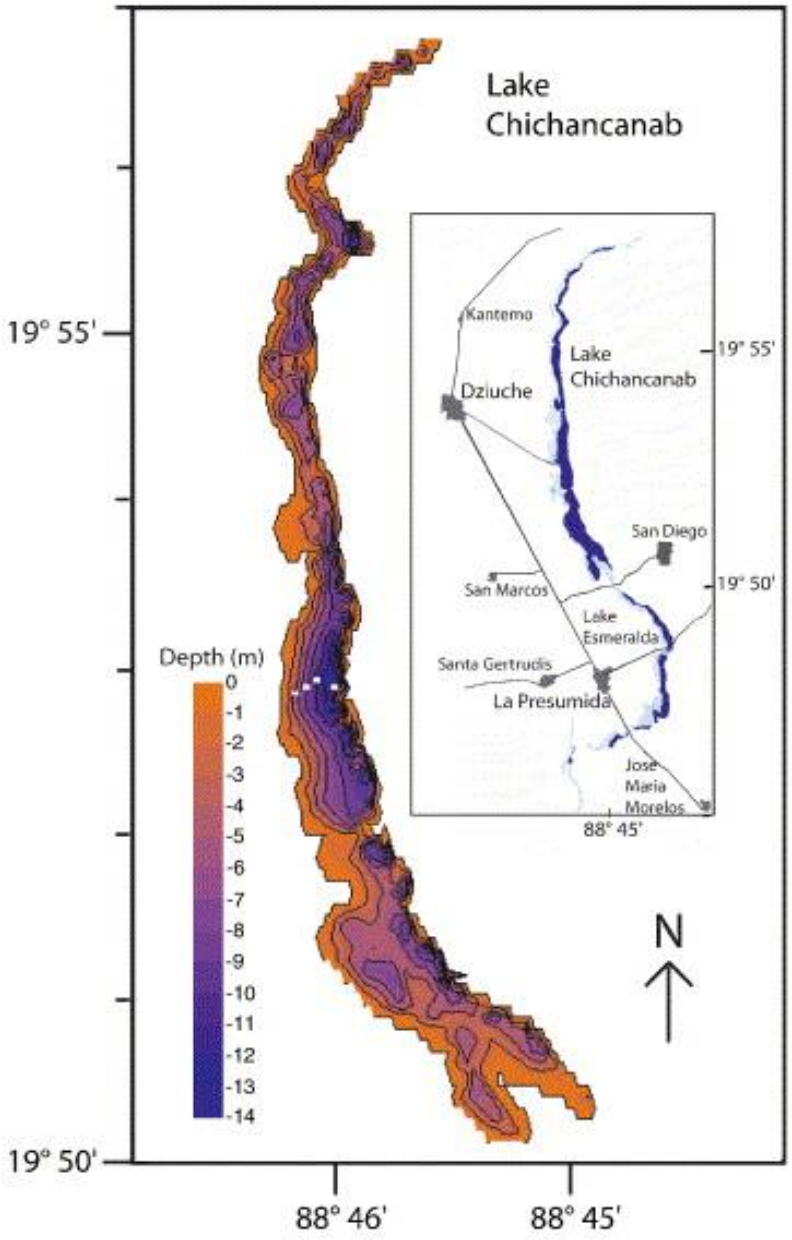

Figure 3.6 Bathymetry of Lake Chichancanab with Laguna Esmeralda shown to highlight the close association between the two lakes(Hodell et al., 2005). It remains plausible that these two lakes were once connected during times of higher water levels (Hodell et al., 2002)

3:6 Core and proxy sampling

3:6:1 Basil Jones

The core for Basil Jones was sub-sampled in its entirety in a clean pollen lab at a 1 cm resolution. Care was taken to ensure all utensils were clean to prevent contamination. Samples were placed in plastic bags and stored in the cold storage. Low-resolution pollen sampling (20/40cm) was completed on the lower (340-200cm, with 40cm between 260-220cm) parts of the core. High-resolution samples were completed at 10cm (190-150;110-90cm), 5cm (135-120cm) and 2cm (82-78cm). The upper parts of the core (60-0cm) was completed the same lower resolution (20cm) as the bottom of the core. The charcoal analysis was undertaken at a 2cm resolution throughout the entire core, with increasing resolution (1cm) recorded around charcoal peaks in the record.

3:6:2 Laguna Esmeralda

Samples for both pollen and charcoal analyses were extracted using a 1cm circumference plastic tube, to ensure the core remained intact for additional proxy analysis not covered in this thesis. Sampling focused on key chronological periods identified by the age-depth model, with the lower 40cms unable to be analysed due to poor pollen preservation. A 20 cm sampling resolution was completed at various parts in the core (347.5-267.5cm, 197-177cm and 96-76cm) with the remainder sampled at 10cm. A higher resolution sampling was completed at 2cms after the age model identified the key chronological periods (60-58cm and 46-36cm). The charcoal preparations and analyses were split evenly between two researchers with the upper 195-1cm completed by the author at Northumbria University and 393.5-196cm completed by a researcher at Nottingham University. Fifteen samples were exchanged between examiners for cross-validation.

3:7 Pollen Preparation for core and surface samples

3:7:1 Pollen preparation

Pollen preparation for all Ambergris Caye, Laguna Esmeralda and Lake Chichancanab samples followed a modified version of the original protocol by Faegri and Iversen (1989), with an additional final sieving stage to allow for the concentration and easier identification of cultigen pollen (Whitney *et al.*, 2012). 1cm^3 of sediment was used, measured via water displacement in a 15cm^3 centrifuge tube. Due to differences in sediment, the core from Ambergris Caye was treated with potassium hydroxide (KOH) in a hot water bath at 90°C. The samples from Laguna Esmeralda and Lake Chichancanab used sodium hexametaphosphate (Calgon) in a 90°C water bath. Following the treatment, samples were sieved at 250µm to remove large macrofossils and washed with distilled water. The large macrofossils from the Ambergris Caye core were kept for radiocarbon dating. All samples were centrifuged, decanted and spun to ensure the solution was completely mixed. To remove carbonates from the residues, samples were completely dehydrated and rinsed with 8cm^3 of hydrochloric acid (HCL). Following observations on the reaction of the HCL to the samples, to ensure no carbonates remained, all samples were treated with a cycle of hydrofluoric acid (HF) to remove silicates. Due to higher proportions of silica materials in the Laguna Esmeralda and Lake Chichancanab samples, they were left longer (4 days) in the HF solution compared to the Ambergris Caye samples (2 days). After two days, the samples had the solution decanted and reapplied to ensure the efficiency of the chemical to dissolve silica. Once the samples were finished their respective time allocation for HF, a rinse cycle of HCL was completed to remove HF. Using litmus paper all samples were tested for HF and an additional rinse cycle of HCL was used if HF remained. After assurances that HF was completely removed from the samples, the acetolysis stage was completed for all samples. Due to acetolysis vigorous reaction with water, a rinse cycle of glacial acetic acid was completed to ensure the samples were completely dehydrated. Following this a solution of nine parts acetic anhydride and one-part sulphuric acid was mixed. Once the acetolysis mixture was completed, the solution was added to the samples and heated in a 90°C water bath for strictly 3 minutes. Following this procedure, the samples were spun and decanted, with a rinse cycle of glacial acetic acid completed removing the solution from the samples.

To prepare the samples for the final sieving stage, all samples were treated with their respected chemical (KOH for Ambergris Caye and Calgon for Laguna Esmeralda and Lake

Chichancanab) and placed in the 90°C water bath. The modified sieving method was then employed, where all samples were sieved at 53µm (Whitney *et al.*, 2012). This measurement was chosen because it was deemed the minimum size of *Zea mays* pollen grains and therefore would speed up the identification of cultigen pollen (Holst, Moreno and Piperno, 2007). Each sample was then separated into fine (< 53µm) and coarse (> 53µm) for analyses. Once all samples were sieved, exotic marker tables (*Lycopodium* batch 3862) were added to both the coarse and the fine materials to calculate concentrations (Stockmarr, 1971). HCL was used to dissolve the tablets and once the reaction was completed, samples were centrifuged and decanted. Due to the reaction that takes place between silicon oil and water, samples were washed with Isopropyl alcohol (IPA), centrifuged and decanted. Samples were then washed into smaller 5 cm^3 glass vials using IPA. The samples were then centrifuged and decanted. Approximately 1-2 cm^3 of silicone oil was added to each sample, dependent on sample volume (more sediment, more oil). Samples were then placed on a heating block (50°C) to evaporate any remaining IPA. Wooden laminae poles were used to stir the samples after six hours in the block. Samples were then left-over night. Pollen samples were then mounted on pollen slides, with paraffin wax used to ensure longer preservation. Due to poor preservation of materials present in two of our surface samples (Esmeralda 7; Chichancanab 3) these were not included in the analysis (Table 3.1). For the surface samples, since no alternate sieving method was employed, *Lycopodium* tablets were inserted at the start of the protocol following standardised methods (Faegri and Iverson, 1989).

3:7:2 Macroscopic charcoal preparation

Methods for preparation of pollen and charcoal sample similar protocol to that identified above (Figure 3.6). Here 1cm^3 of sediment was measured per sample via water displacement. Samples were treated with their respective chemical solution (KOH for Ambergris Caye and Calgon for Quintana Roo) and placed into a 90 °C water bath for 4 minutes (Clark and Patterson, 1997; Whitlock and Larsen, 2001). Samples were then sieved using a modified sieving device at 250µm (coarse) and 125µm (fine). All samples were washed with distilled water and transferred into 50 ml tubes for analysis.

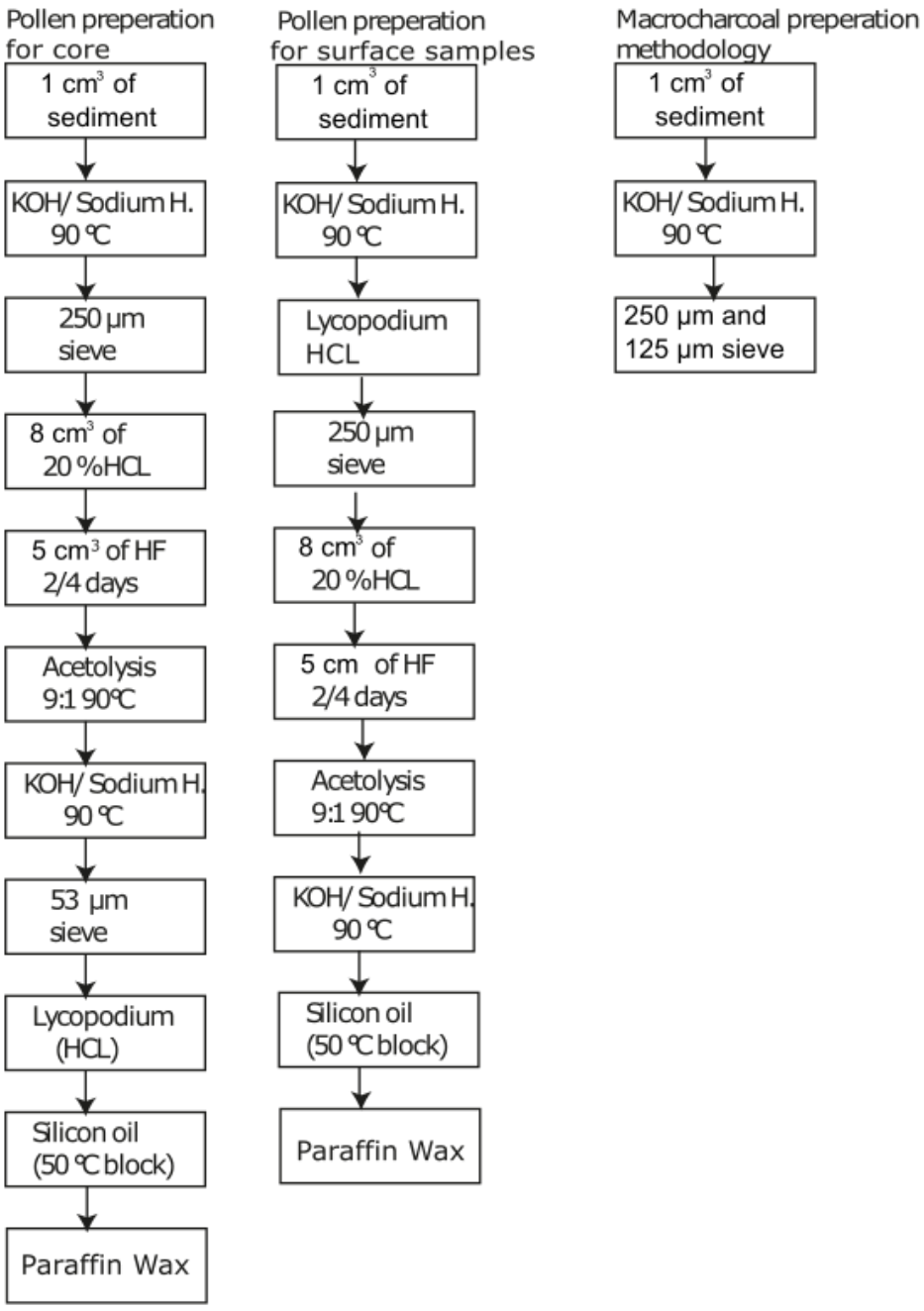

Figure 3.7 Methodology employed for the preparation of pollen and charcoal. The methods for the surface samples are also illustrated due to differences in the stage in which lycopodium was added

3:8 Counting

3:8:1 Pollen counting

A standard limit of >200 pollen grains were counted for samples in both cores, with low pollen preservations and concentrations restricting higher counts (full counts per sample available on Appendix A Table 1). Using Maher's lognormal distribution in the Psimpoll computer software (Bennett, 2005) 95% confidence intervals were plotted to ensure that the minimum pollen counts captured the variance in abundances across the samples (Maher, 1971) (Appendix A). Grains were examined at 400× and 1000× magnification using a Leica DM2000 microscope. Pollen identification was achieved with the use of mounted reference atlases at the University of Northumbria and additional reference atlases (Palacios-Chavez, Ludlow-Wiechers and Villanueva, 1991; Pena-Chocarro, Knapp and Brokaw, 2011). Identification of pollen grains was achieved at a minimum of family-level taxonomic resolution, with higher resolution achieved with the aid of reference atlases (Burn and Mayle, 2008; Mao *et al.*, 2012; Gosling, Miller and Livingstone, 2013; Mitchell and Daly, 2015). The identification of *Zea may*s from separate species of the Poaceae family was achieved through the relative size of the grain and the unique exine characteristics (Holst, Moreno and Piperno, 2007). A minimum of 150 pollen grains were counted from the surface samples, with the 95% confidence intervals similarly plotted (Appendix A).

3:8:2 Charcoal counting

Charcoal counting was completed using a binocular stereoscopic microscope (Nikon) and a gridded petri dish. All charcoal was counted from the original 1cm³ sample. Counts were originally separated between coarse (>250µm) and fine-grained (125-250µm) charcoal particles to determine the local from the regional signals of fire, however, this was later combined for the statistical processing described below. Charcoal identification used standard identification techniques in which black and opaque objects were classified as charcoal (Faegri and Iversen, 1989; Mustaphi and Pisaric, 2014).

3:9 Numerical and Statistical analysis

3:9:1 Pollen statistical analyses

Using the Psimpoll software (Bennett, 2005), numerous statistical analyses were applied to the pollen abundance data. All data were transformed into proportions and analysed, based on software recommendations. Zonation of the pollen assemblages, by depth, was required to determine statistically significant splits in the data. Pollen counts from the Ambergris Caye core were transformed via the square root transformation and zoned via the binary sum of squares (Bennett, 1996). For Laguna Esmeralda, the dataset was also transformed using the square root transformation and zoned via the optimal sum of squares method (Bennett, 1996). To determine the most efficient method of zoning and transformation, a parameter test was completed on both datasets. Testing all individual transformation and zoning combinations, the combined method, which produced the most statistically significant splits were selected for analysis (Appendix A). Stratigraphy plots were constructed in the C2 software (Juggins, 2007).

3:9:2 Charcoal Statistical methods

To test the statistical importance of the raw charcoal record and to determine whether the record identifies a signal or components of background charcoal, the raw charcoal dataset was reanalysed in the CHARanalysis software (Higuera, 2009; free-ware available at http://phiguera.github.io/CharAnalysis/). Using years calibrated BP per cm^3 (calculated by dividing the interpolated charcoal concentrations by the time interval), the raw charcoal samples (C) (combined coarse and fine records) were binned into a site-specific time window. Similar to the pollen zonation, a series of parameter tests were ran. A series of runs were completed, altering the time interval, to capture the highest proportion of time

windows which showed a signal to noise (SNI) >3 and a goodness of fit greater (GOF) than 0.9. When SNI is >3, the charcoal reanalysis is said to capture significant peaks in the record, with values below this threshold likely representing background noise *(Higuera et al*. 2010; Kelly *et al*. 2011). Identification of low-frequency variations of charcoal influx or the background component of charcoal (BCHAR) were identified using a smoothing algorithm. Both the Ambergris Caye core were smoothed via a Lowess method, which was robust to outliers. Varying smoothing windows and fire frequency-time window were also established differently for the Ambergris Caye (smoothing = 1200 years, ff = 1200 years) and the Laguna Esmeralda (smoothing = 700 years, ff = 800 years) cores (Table 3.2). Details of full parameter testing are also available (Appendix A).

Table 3.2 Parameter choice for CharAnalysis software for Laguna Esmeralda and Basil Jones

Site	**Smoothing**	**Years to smooth record (years)**	**Locally / Globally defined threshold**	**Fire Frequency (smoothed over) (years)**
Basil Jones	Lowess (robust to outliers)	1200	Locally	1200
Laguna Esmeralda	Lowess (robust to outliers)	700	Locally	700

3:10 Selection of material for ^{14}C dating

3:10:1 Ambergris Caye

To establish the relationship between age and depth in the Ambergris Caye and the Laguna Esmeralda cores, radiocarbon (^{14}C) dating was chosen. The availability of terrestrial macrofossils allowed for eight samples to be dated from the Ambergris Caye core. Aquatic and mangrove macrofossils were avoided when possible due to the uncertainties associated with the respective materials. Mangrove roots potentially bury deep in sediment, which would produce younger ^{14}C ages in the sediment horizon (Woodroffe *et al.*, 2015), whilst aquatic plants do not obtain their carbon directly from the atmosphere and could potentially be offset by the hardwater effect, producing older than anticipated radiocarbon dates (Schiffer, 1986; Hanna *et al.*, 2016). Partially burned macrofossils were accepted when required. Eight samples were sent to the NERC radiocarbon facility in Glasgow and one sample to the Silesian Institute of Technology, Poland (Table 3.3)

3:10:2 Laguna Esmeralda

The lack of available macrofossil suitable for radiocarbon dating from the Laguna Esmeralda core resulted in bulk sediments being sent for analysis. The uncertainty associated with the dating of bulk sediments is obtained from the possible absorption of underlying calcareous bedrock into the sediment, resulting in significantly older 14C dates (Schiffer, 1986; Hanna *et al.*, 2016) To account for this 'old carbon' influence, surface sediment was sent for radiocarbon dating. An assumption was made that the surface sample would be modern (i.e. 2016 at the time of collection) and the old carbon effect could be calibrated by obtaining the ^{14}C date from this surface sample and finding the difference between the ''true'' date and the ^{14}C date. Five bulk sediment samples, with shells removed to avoid further contamination of old carbon, were sent to the NERC radiocarbon institute in Glasgow (Table 3.3).

Table 3.3 List of samples sent for radiocarbon analysis to the NERC radiocarbon facility (UK) and the Silesian Institute of Technology (Poland).

Publication Code	**Study Site**	**Sample Depth (cm)**	**Material Selected**
SUERC-84523	Basil Jones	14	Terrestrial twig
SUERC-83474	Basil Jones	50	Bark Fragment
UCAIMS-210606	Basil Jones	100	Plant Macrofossil
UCAIMS-210617	Basil Jones	126	Terrestrial leaf pieces
SUERC-81082	Basil Jones	165	Outer bark*
SUERC-81806	Basil Jones	225	Wood
SUERC-81807	Basil Jones	240	Charcoal*
SUERC-81808	Basil Jones	290	Terrestrial burnt twig*
GdA-5491	Basil Jones	302	Plant Macrofossil
SUERC-75747	Laguna Esmeralda	0-3	Bulk sediment picked of shells
SUERC-75751	Laguna Esmeralda	46.25	Bulk sediment picked of shells
SUERC-75752	Laguna Esmeralda	94.75	Bulk sediment picked of shells
SUERC-75753	Laguna Esmeralda	144.25	Bulk sediment picked of shells
SUERC-82294	Laguna Esmeralda	387	Bulk sediment picked of shells

*materials potentially impacted by re-deposition

3:11 Analysis of surface sample data

3:11:1 Spatial Analysis

For the analyses of the surface pollen dataset from Laguna Esmeralda and Lake Chichancanab, a representation of total forest cover was required. Estimations of total tree cover were extracted from the Landsat global forest change 2000-2014 study (Hansen *et al.*, 2013). A 10 x 10-grid cell was extracted (10-20N, 90-100W) to gather data on regional forest cover (Hansen *et al.*, 2013). In this analysis, the year 2000 tree cover data was deemed viable as an appropriate representation of the contemporary forest cover (Figure 3.4). Tree cover in 2000, was defined as canopy closure for all vegetation taller than 5m in height (Hansen *et al.*, 2013). All water features were masked, to prevent the association of water as not forest. Using the buffer tool in ArcGIS, a geometric series of buffers at 100, 500, 1000, 3000 and 7000m were created around each surface sample. From here, the zonal statistics as table tool in GIS extracted mean and percentage of total forest cover represented in each of these buffers. Other variables such as distance to nearest forest cover and distance to shore were measured for each sample point in ArcGIS.

3:11:2 Ordination Techniques

Ordination analysis was used to determine the relationship between the created buffers, variables selected (distance to forest/shore) and the modern pollen assemblage. Additional buffers were originally included in this investigation, but an examination of the correlation between the variables required numerous larger buffers to become removed. Despite correlations still existing between the variables from 3000-7000m (-0.92), both variables were included because they represent an important component of the percentage forest dataset. Detrended correspondence analysis determined that a short environmental gradient existed (Appendix A) between the variables and thus a Principal Component Analysis (PCA) and Redundancy Analysis (RDA) analysis was completed. All pollen data were transformed using the Hellinger transformation (square root) and plotted in the R package ‘’vegan’’ (Oksanen *et al.*, 2018). This transformation was completed to compensate for over-representative species. Redundancy analysis plotted the transformed pollen data against the buffers (100, 500, 1000, 3000, 7000m) mean forest cover and the distance to forest/shore for each surface sample point. To understand the independent significance of the environmental variables in driving the signals recorded in the modern pollen surface

samples, each variable was tested for its significant contribution through an ANOVA test. PCA diagrams were also constructed for both the long cores of Laguna Esmeralda and Basil Jones, to aid in the groupings of the vegetation based on ecological similarities (Appendix A)

3:11:3 Use of existing datasets

To understand the relationship between the modern pollen assemblages and the palaeoecological record from Lake Chichancanab, a reinterpretation of the existing palaeoecological record was completed (Leyden, 2002). A “clam” age model was constructed in a similar process to the Laguna Esmeralda sediment core to allow for comparisons between the two fossil pollen records. Despite recent palaeoclimate investigations being completed from Lake Chichancanab (Brenner *et al*., 2002; Hodell *et al*., 2005; Brenner *et al*., 2018), the samples for constructing the age model was based on the authors' original methods which used the Hodell *et al*., (1995) sediment core (Leyden, 2002). This was due to no information being available for the proximity of the 1995 sediment core to the more recent investigations, and therefore an age-depth relationship could not be established based on more recent results.

3.12 Author contributions and acknowledgements

This chapter was written by Adam Bermingham who undertook all the laboratory work and analytics of the data. Sample collection for the Ambergris Caye core (Basil Jones) was completed by Dr. Bronwen Whitney before the start of this PhD. Surface samples and cores were taken from Quintana Roo (Laguna Esmeralda and Lake Chichancanab) was completed by Dr. Sarah Metcalfe and students from Nottingham University in the U.K. Samples for radiocarbon dating was selected by Adam Bermingham for the Basil Jones core, with the Esmeralda core selected by colleagues at Nottingham University.

Chapter 4 A first palaeoecological investigation into Maya land-use on an island site, Ambergris Caye (Belize)

4:1 Overview

This chapter analyses the palaeoecological record from the island of Ambergris Caye, Belize. Using a combination of pollen and charcoal proxies, the record identifies over 5000 years of ancient Maya land-use. Located within the seasonally dry tropical forest ecosystem, the site of Basil Jones was selected for this analysis. The record establishes the first evidence for cultivation on the island, predating archaeological evidence for initial occupation. Correlations are established between patterns of climate drying and increasing land-use on the island, potentially indicating the growing importance of island sites as refuges during periods of instability.

4:2 Introduction

The decline of the Classic Maya civilisation has been attributed to a variety of environmental and social factors, with high-resolution palaeoenvironmental records revealing the strong influence of climate change on these underlying factors (Kennett *et al*., 2012; Turner, 2012; Hoggarth, 2016). Whilst the social impacts of these drought events are becoming evident, little attention has been paid to understand how subsistence strategies were modified or adapted to respond to climatic changes. Palaeoecological investigations have addressed questions regarding Maya subsistence and landscape management, such as the first establishment of agriculture (Pohl *et al.*, 1996; Dunning *et al.*, 1998; Rosenswig *et al.*, 2014), the degrees of deforestation associated with the growth of their civilisation (Leyden, 2002; McNeil, 2012) and ecosystem response following the abandonment of settlements (Wahl *et al.*, 2007; Mueller *et al.*, 2010; Turner and Sabloff, 2012). Whilst these studies have furthered our understanding of how the ancient Maya interacted with their environment, previous studies have focused on the mainland settlements of the central and southern lowlands. To date, no research has attempted to use palaeoecological proxies to reconstruct ancient Maya land-use on island sites.

Following periods of mainland instability during the Preclassic abandonment (*ca* 250 CE) and decline during the Terminal Classic (between 750-1100 CE), activity towards the coast increased (Miller, 1985; McKillop, 2010; Cucina, 2015), likely indicating new patterns of subsistence use. Island such as Ambergris Caye and Cozumel saw increasing activity during the Postclassic (*ca* 1200 CE) (Guderjan, 1995; Rathje and Sabloff, 2010), with settlement on Ambergris detected during the Preclassic (*ca* 600 BCE) (Guderjan, 1995; Graham *et al.*, 2017). The development of sophisticated trade networks along the coast and interior rivers have driven the narrative of occupation and use of these island sites (Graham, 1989; Guderjan, 1995; Graham *et al.*, 2017). The smaller island settlements provide an important opportunity to understand how these less densely populated communities managed the landscape, especially during times of mainland instability.

The understanding for subsistence on island sites is provided by archaeological evidence that shows inhabitants had high-marine based diets with some degree of maize consumption (Williams, White and Longstaffe, 2005; Parker, 2011; Graham *et al.*, 2017). The source of this maize is argued to have come from well-established trade networks, with the vital terrestrial crop imported from the mainland, due to unavailable local environments capable of cultivation (Parker, 2011; Graham *et al.*, 2017). Given the increased importance of maritime exchange and well-established relationship between the island and the mainland, this chapter will investigate how the small density populations of the ancient Maya were using the landscape, particularly during times of mainland abandonment (Preclassic abandonment/Terminal Classic).

4:3 Methods and site summary

The Ambergris Caye archaeological project identified up to twenty-two archaeological sites located around the island (Guderjan, 1995) (Figure 4.1). The sinkhole cored for this analysis was located close to the archaeological site known as Basil Jones, which is located in the northern dry forest ecosystem and archaeological interpretations suggesting a Postclassic occupation (*ca* 1200 CE). To investigate the land-use strategies of the ancient Maya on an island site, a combination of fossil pollen and charcoal have been analysed. Statistical analysis of the pollen zonation saw the samples zoned through the binary sum of squares and transformed via a square root transformation. Full site descriptions, methods summary and archaeological context are provided in Chapter 3. Palaeoecological interpretations of the pollen found in this record are highlighted in Table 2.2. For the vegetation groupings, a PCA diagram was produced to show some scale of similarities

between the taxa identified Appendix A. Table 4.1 shows the breakdown of the vegetation groupings along with the palaeoecological interpretation

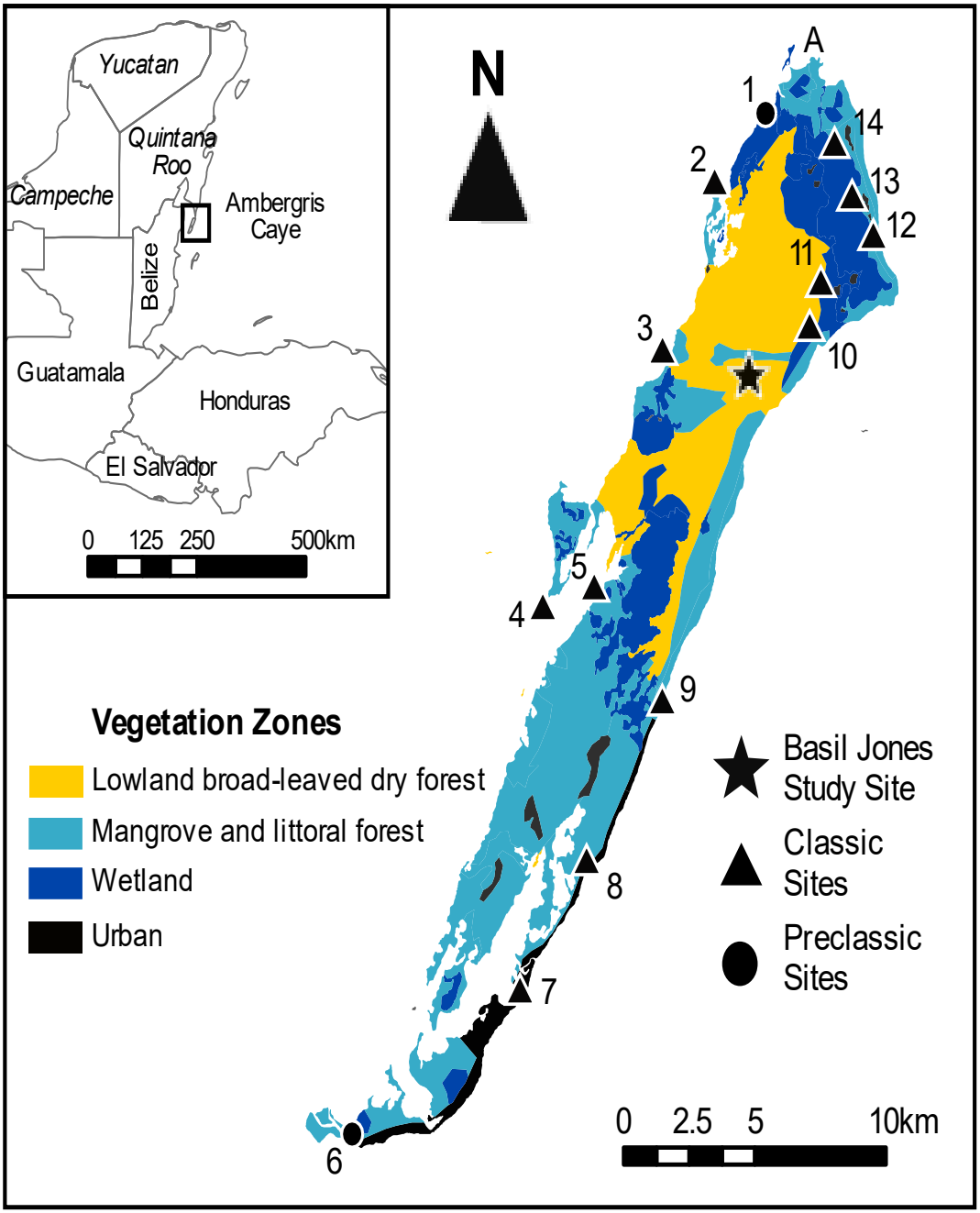

Figure 4.1 Map of Ambergris Caye, Belize. Vegetation zones are taken from Meerman (2004). Archaeological sites are from Guderjan (1995) and Graham et al. (2017). 1. Chac Balam, 2. San Juan, 3. Santa Cruz, 4. Yalamha, 5. Laguna de Cayo Francesca., 6. Marco Gonzalez, 7. San Pedro, 8. Tres Cocos, 9. Los Renegados, 10. Robles Point, 11. Burning Water, 12. Franco, 13. Valencia, 14. Ek Luum, A. Boca Bacalar Chico

Table 4.1 Table of ecological groupings, palaeoecological interpretations and ecological assignments (SDTF= seasonally dry tropical forests) for pollen types identified in the Basil Jones core. Palaeoecological interpretations are based off a combination of the PCA diagram (Appendix A) and also the ecological and vegetation description highlighted in Chapter 2.

Taxa identified	**Vegetation grouping in pollen diagram**	**Paleoecological interpretation**	**Ecological assignment**
Brosimum	Trees and Shrubs	Primary forest/potential anthropogenic	SDTF
Ficus	Trees and Shrubs	Primary Forest	SDTF
Maclura.	Trees and Shrubs	Primary Forest	SDTF
Solanaceae	Trees and Shrubs	Primary forest/potential human indicator	SDTF but also present in other ecosystem types
Anadenanthera	Trees and shrubs	Forest species	SDTF
Arecaceae	Trees and shrubs	Forest/potential human indicator	SDTF but also present in a range of ecosystem types
Spondias	Trees and shrubs	Forest/potential human indicator	SDTF
Anacardiaceae	Trees and Shrubs	Forest vegetation	SDTF

Betulaceae	Trees and Shrubs	Forest vegetation	SDTF
Ulmus	Trees and Shrubs	Forest vegetation	SDTF
Quercus	Trees and Shrubs	Forest vegetation	SDTF but also present in savannah ecosystems
Pinus	Trees and Shrubs	Likely long-distance transportation	Likely savannah ecosystem
Acalypha	Trees and Shrubs	Forest vegetation	SDTF
Guazuma	Trees and Shrubs	Forest vegetation	SDTF
Alnus	Trees and Shrubs	Forest vegetation	Likely long-distance transported from highland regions
Boraginaceae	Trees and Shrubs	Forest vegetation/potential shrubs	SDTF
Metopium brownei	Trees and Shrubs	Forest vegetation	SDTF
Piscidia	Trees and Shrubs	Forest vegetation	SDTF
Acacia	Trees and Shrubs	Disturbance indicator	SDTF
Fabaceae	Trees and Shrubs	Forest vegetation	Present in a range of ecosystems

Combretaceae/Melastomataceae	Trees and shrubs	Wetland indicator as per this study	Also present in savannah ecosystems
Sapium	Trees and Shrubs	Forest vegetation	SDTF
Borreria	Trees and shrubs	Quick coloniser species/disturbance indicator	SDTF but also present in savannah ecosystems
Celtis	Trees and Shrubs	Secondary taxa/early coloniser	SDTF
Myrica	Trees and shrubs	Secondary taxa/early coloniser	SDTF
Gymnopodium	Trees and shrubs	Shrub vegetation	SDTF
Bursera simaruba	Trees and Shrubs	Early coloniser species	SDTF
Mimosa	Trees and Shrubs	Disturbance indicator, shrub species	SDTF, savannah, open landscapes
Poaceae	Herbs	Disturbance/openness indicator and interpreted to be from the same terrain as the seasonally dry tropical forest	Wetland and savannah
Asteraceae	Herbs	Disturbance/openness indicator in SDTF	SDTF but present in a range of disturbed environments
Chenopodiaceae/ Amaranthaceae	Herbs	Disturbance/openness indicator in SDTF	SDTF but present in a range of

			disturbed environments
Cyperaceae	Herbs	Disturbance/openness indictor	Wetland and savannah
Rhizophora mangle	Mangrove	Mangrove indicator	Likely from coastal parts of the island
Avicennia Germinans	Mangrove	Mangrove indicator	Likely from coastal parts of the island
Bravasia tubiflora	Mangrove	Mangrove indicator	Likely from coastal parts of the island
Acrostichum aureum	Mangrove fern	Mangrove indicator from coastal parts of the island	Likely from coastal parts of the island
Sagittaria	Aquatic vegetation	Potentially linked to sinkhole hydrology	Likely reflecting local vegetation
Typha	Aquatic vegetation	Potentially linked to sinkhole hydrology	Likely reflecting local vegetation
Spathiphyllum (genus identification)	Aquatic	Aquatic vegetation	Likely reflecting local vegetation

4:4 Results

4:4:1 Age-depth model

Radiocarbon dates from the nine samples were corrected to account for changes in ^{14}C concentrations in the atmosphere using the northern hemisphere IntCal13 calibration curve and Post-Bomb northern hemisphere 2 (Reimer *et al.*, 2013). Using the smoothing spline method, the age model was constructed using the R computer software package ''clam'' (Blaauw, 2010a, 2010b) (Figure 4.2). A lack of available material at the base of the core resulted in the lower sediments being extrapolated down core from the last radiocarbon date at 302cm. Of the nine dated samples, two dates showed a degree of reversal. One reversal at 165cm (1192 ± 37 BP) was excluded from the analyses. The second age reversal at 240cm (4335 ± 37 BP) was included as the mean age was within the range of uncertainty associated with the construction of the curve.

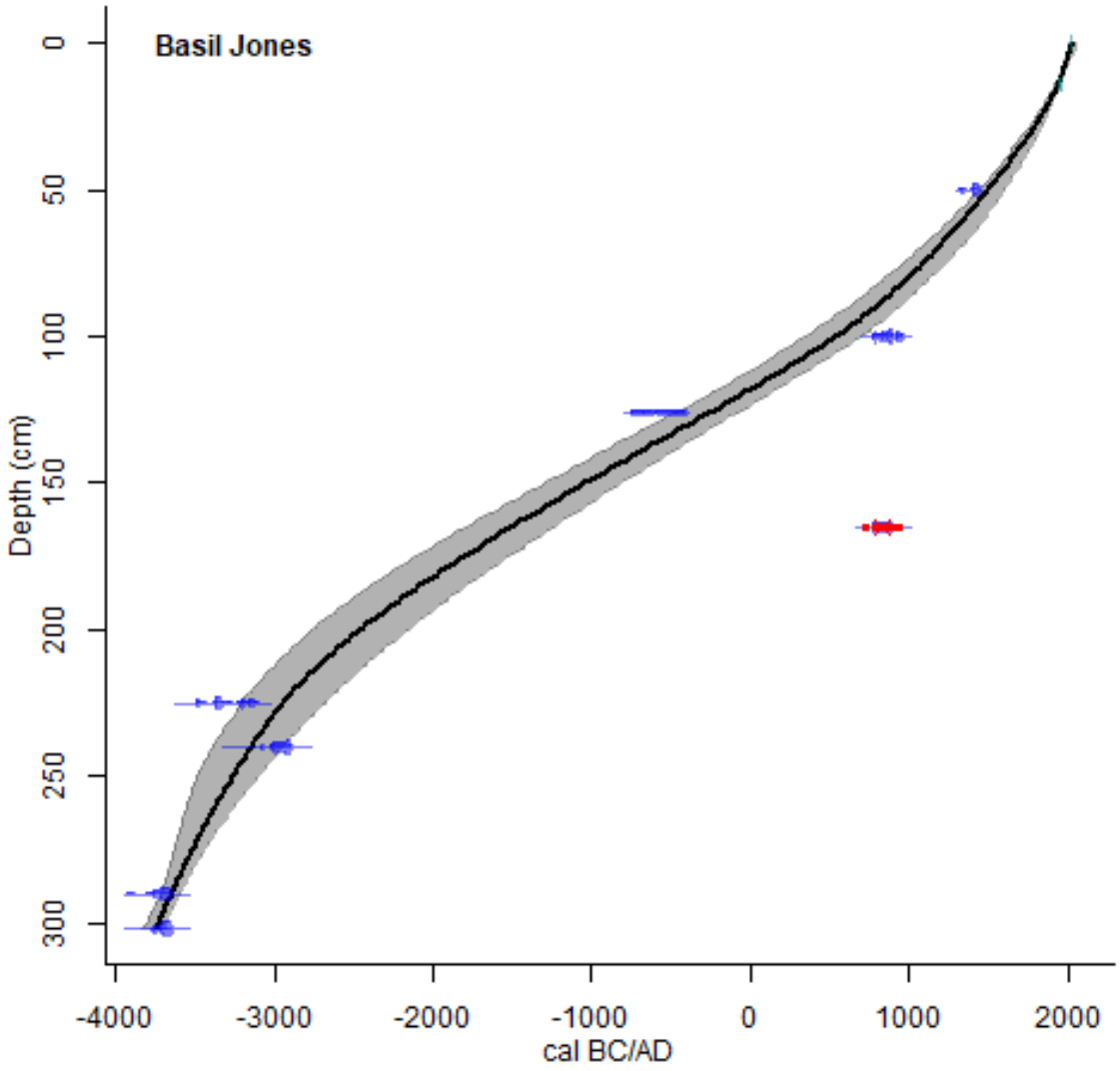

Figure 4.2 Age depth relationship produced by radiocarbon recalibration using the IntCal13 calibration curve. Ages are produced to 2-sigma uncertainty ranges (95th percentile) and presented in BCE/CE. The red star indicates one rejected age.

4:4:2 Palaeoecological analysis

Zonation of the microfossil pollen record produced four statistically significant zones. The identification of a one-sample zone at the base of the core (340cm) resulted in this being combined with the next adjacent zone (320-280cm) and named BJ-1. The three zones were then numbered sequentially (BJ-1 to BJ-3) (Figure 4.3).

Results of the CharAnalysis reconstruction are presented with the pollen zones (BJ1-BJ3). Key results described are peak events that passed the 95% threshold (including magnitude) and fire frequency per 1200 years (Figure 4.5).

4:4:2:1 BJ-1: 340-280cm (5.9-5.5 kyr cal. BP/ ca 4200-3600 cal. BCE) (4 samples)

From *ca* 4000 BCE, the abundance of pollen is dominated by Cyperaceae (65%) and mangrove associated fern *Acrostichum aureum* (>100%). This zone is dominated by these ferns along with indicators of a wetland/mangrove local environment. Per cent abundances gradually decrease throughout the zone. Forest indicators Moraceae/Urticaceae and openness indicator Poaceae increase in abundance from 4000-3400 BCE. High abundances of *Sagittaria* pollen, indicative of aquatic vegetation (>100%), is recorded in one sample (4000 BCE) and then becomes absent. CharAnalysis shows five fire events between ca. 4000-3600 BCE, with one peak showing a high magnitude of 148 $cm^{-2}yr^{-1}$. Fire frequency is constant at six fires per 1200 years throughout the zone.

4:4:2:2 BJ-2: 260-135cm (5.2 - 2.5 kyr cal. BP / ca 3600-800 cal. BCE (10 Samples)

BJ-2 signifies the first recorded presence of *Zea mays* in the record at 2960 BCE (1 σ STD: *ca* 2700-3250 BCE). Abundant *Acrostichum.* (12%) and Cyperaceae (16%) is recorded at 2100 BCE and 3200 BCE, respectively, and subsequently declines to negligible values. Following a relatively high abundance of forest pollen Moraceae/Urticaceae at *ca* 3200 BCE (64%), there is a continued decrease of the pollen, reaching a minimum at *ca* 700 BCE (24%). The declining of the previous mangrove/wetland indicators results in the high pollen abundances of seasonally dry tropical forest vegetation. Increasing in potential fringe vegetation Combretaceae/Melastomataceae also dominate this zone. This decrease is mirrored by increases in Fabaceae (~10%) and Solanaceae (~5%) abundances between *ca* 2800-500 BCE. Between *ca* 3200-2000 BCE, a continuous increase in Combretaceae/Melastomataceae pollen is recorded (2-16%) through this zone. Poaceae abundances decreases from 19% *ca* 1300-500 BCE. The disturbance indicators *Mimosa* (17%) and Asteraceae (1%) fall from *ca* 300 BCE through the remainder of the zone.

The charcoal data shows 5 fires that pass the 95% threshold, but none record a higher magnitude than 10 $cm^{-2}yr^{-1}$. Fire frequency varies from five fires to one fire per 1200 years, peaking at the top of the zone.

4:4:2:3 BJ-3: 132.5-0cm: 2.4 kyr cal. BP- present/ 800 cal. BCE- present (13 samples)

BJ-3 shows the highest recorded presence of *Zea mays* in the record at three different points (best estimate *ca* 300 CE, 1200 CE and 1760 CE). Increases in human indicators (cultivation and fire activity) result in the declines of Combretaceae/ Melastomataceae, with seasonally dry tropical forest vegetation continuing to dominate the pollen assemblages. Combretaceae/Melastomataceae falls to abundances <1% for the remainder of the record. Poaceae (33%) and *Mimosa* (17%) are recorded in high abundances at 50 BCE and 200 BCE, respectively. In both curves a gradual decrease in abundance is recorded, before Poaceae (~15%) remains consist for the remainder of the record. *Mimosa* remains consistent at *ca* 50 BCE to 800 CE (~5%) and then increases above 10 % (max = 18%) until 1000 CE, where it falls below 10% for the remainder of the record. Moraceae/Urticaceae shows high abundances of above 50% throughout the majority of this zone, with low points recorded between *ca* 300 BCE-250 CE (45%) and *ca* 800-1000 CE (~37%). *Sagittaria* is consistently present from 500 CE to the top of the core (~8 %). Seven fire events are recorded through BJ-3/ Two high magnitude fire events (86 and 80 $cm^{-2}yr^{-1}$) are recorded approximately 70 years apart. Fire frequency ranges from 4-1 fire per 1200 years and declines towards the top of the zone.

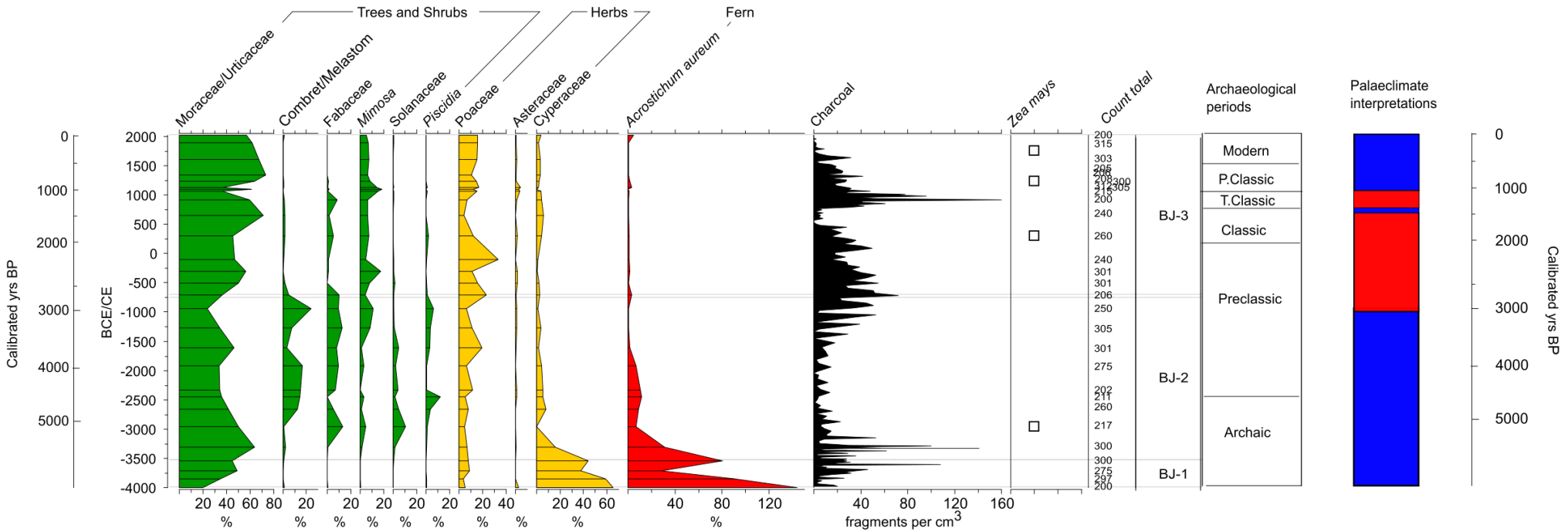

Figure 4.3 Percent abundance for the Basil Jones core. Zea mays indicate the presence of maize pollen from these levels and do not indicate abundance or intensity of agriculture. Charcoal concentrations are included for land-use context. Ecological categories (Trees and Shrubs, Herbs, Ferns) were colour coated for illustration. Total pollen counts and concentrations per cm^3 are also displayed. Ancient Maya periods are also highlighted with T.Classic = Terminal Classic and P.Classic = Postclassic. Palaeoclimate interpretations are based off general trends of the Macal Chasm (Akers et al., 2016) and the Yok Balum speleothems (Kennett et al., 2012) as these are the closest palaeoclimate records to the island. Red indicates general drying trends whilst blue indicates increasing wetness

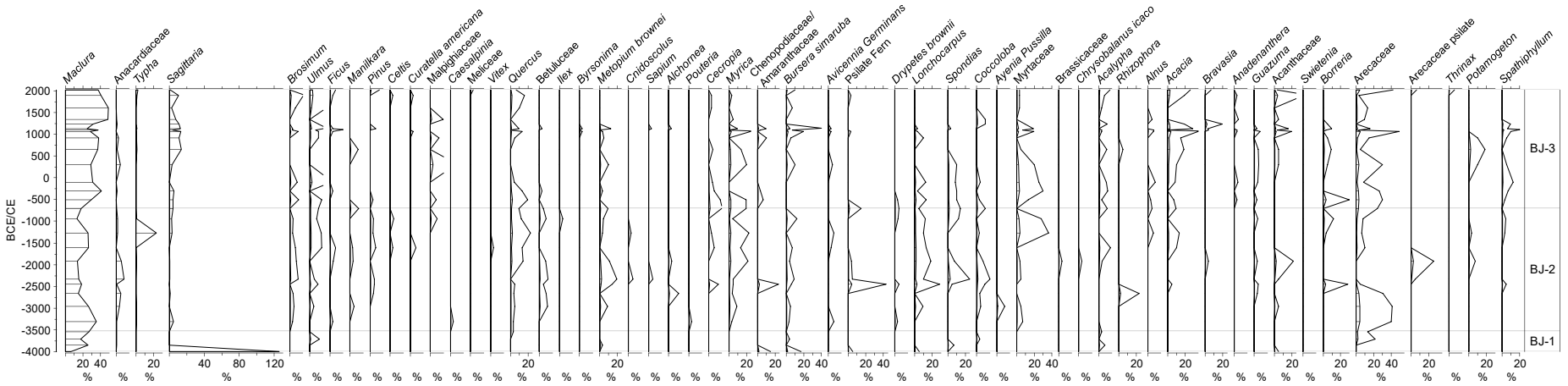

Figure 4.4 Percentage abundance for pollen assemblages not included in the main diagram from the Basil Jones core. x10 exaggerator lines were used for the low abundant species. Percentage abundances of taxa, which composed the Moraceae/Urticaceae assemblage are shown individually (Maclura, Brosimum, Ficus)

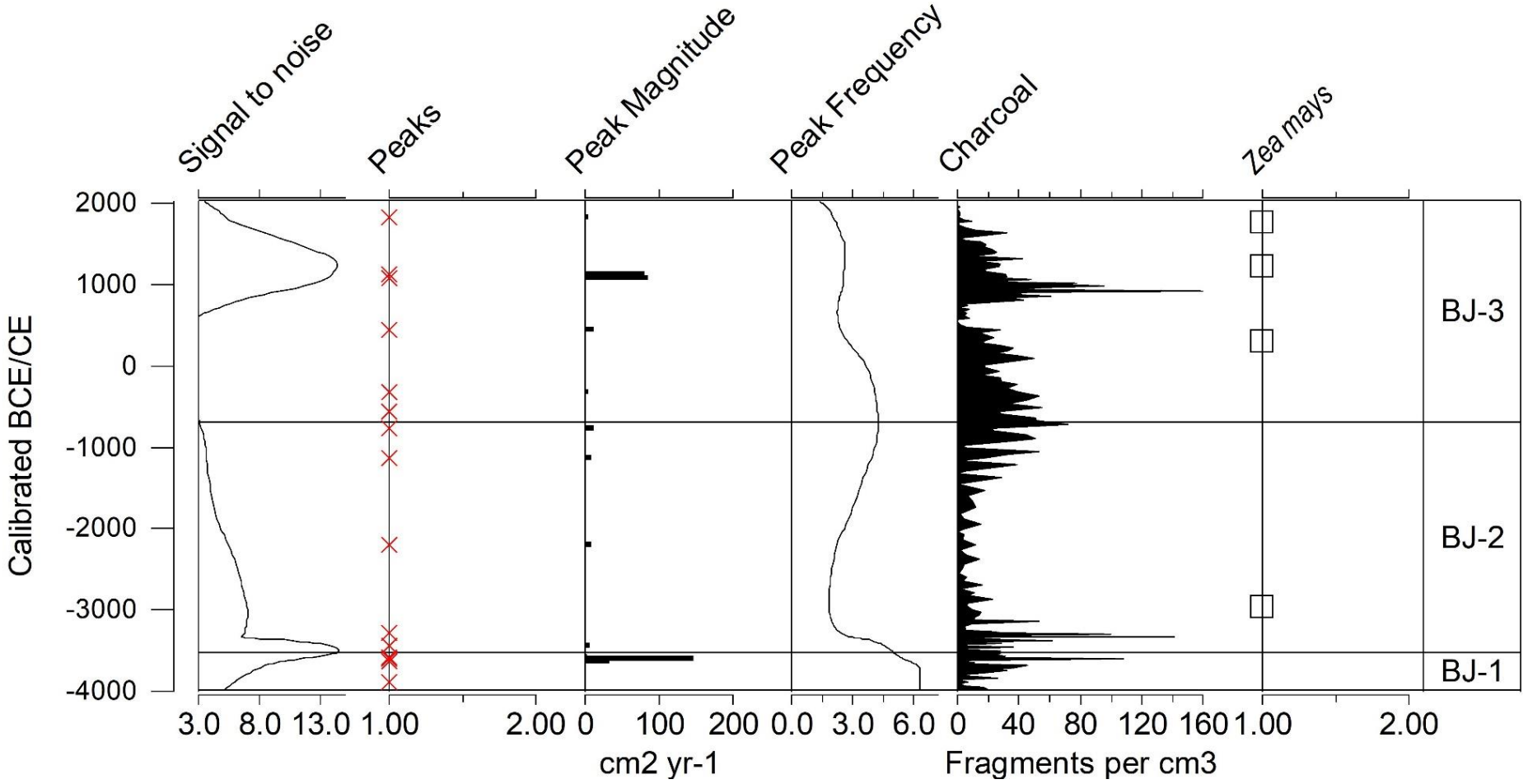

Figure 4.5 Results of the CharAnalysis statistical method. (X) represents detectable peaks that pass the 95% threshold and when SNI >3. Fire frequency (per 1200 years) and peak magnitude also represented. Results described via pollen zonation (BJ-1- BJ-3). Presence of Zea mays are shown for land-use context

4:5 Discussion

The selection of terrestrial macrofossils removed much of the uncertainty previously discussed regarding the hard-water influence and impact of mangrove roots and vegetation. The material from sample 165cm, which was excluded from the model due to the age-reversal recorded, was a piece of outer-bark and therefore was potentially re-deposited, explaining the older age recorded. The partially burned twig sample (290cm) also has the risk of being potentially re-deposited but showed a linear age-depth relationship and was therefore accepted.

From a vegetation perspective, pollen from the family of Moraceae/Urticaceae is interpreted as primary forest taxa, with Combretaceae/Melastomataceae thought of as some degree of fringe vegetation, due to the close association between changes in mangrove indicator (*Acrostichum aureum*). These abundances may also reflect some degree of wetland indicator, as the removal of the local ferns allowed pollen from the coastal parts of the island to be easily deposited into the small sinkhole. Typical grasses (Poaceae) and aster (Asteraceae) pollen are interpreted as openness/disturbance indicators, due to their prevalence to occupy disturbed landscapes. *Bursera* and *Celtis* are also an early coloniser species and therefore the abundances recorded are interpreted to reflect openness in the forest landscape. Full details of ecological interpretations are shown in Table 2.1, Table 2.2 and Table 4.1 respectively.

4:5:1 Ecological influence of the ancient Maya at Basil Jones

The palaeoecological record at Basil Jones shows evidence for a close relationship between periods of fire activity, the presence of cultigen pollen (*Zea mays*) and trends in the abundances of key ecological indicators. The synchronicity between these three variables (fire, cultigens and arboreal pollen abundances) supports our interpretation that the major driver of ecological change at the study site, Basil Jones, was human landscape management.

The first appearance of cultigen pollen at *ca* 2900 cal. BCE occurs after the highest period of fire activity recorded in the record (notably from zone BJ-1). With almost 800 years between the highest peak recorded in the record (~3600 cal. BCE) and the appearance of cultigen pollen, it is difficult to directly attribute this fire signal as strictly anthropogenic in

origin. However, the poor preservation and generally low concentrations of pollen towards the base of the core potentially limited the ability to detect maize cultivation earlier than 2900 BCE. The increasing fire activity occurs in the same sequence as a decline in the mangrove indicator fern, *Acrostichum aureum*. Along with this decline in ferns, aquatic vegetation *Sagittaria* also decreases. Based on the decline in the aquatic vegetation, natural drivers (changes in sinkhole hydrology) for this decline in *Acrostichum* cannot be ruled out but could be strongly linked with the fire record at this period. Following this period of cultivation, from 2500 cal. BCE the absence of cultigen pollen, declining fire activity and the establishment of Combretaceae/Melastomataceae, is interpreted as declining anthropogenic land-use. This is based on the hypothesis that the increase in Combretaceae/Melastomataceae is an indication of limited anthropogenic activity allowing it to dominate and colonise the landscape in a similar stature as the modern landscape.

Due to the lack of archaeological evidence from this period of settlement (~2900 cal. BCE), it is difficult to define the driver of the abandonment. This evidence is argued that the decreasing management of the dry forest ecosystem represents a reorganisation towards the coast of the island. With the earliest evidence for constructed settlement on the island provided by Marc Gonzalez (~600-300 BCE) (Graham *et al.*, 2017), the decreasing management at Basil Jones may indicate an increasing priority towards the coastal, marine-based, settlements. The next detectable period of anthropogenic land-use is associated with the appearance of *Zea mays* at *ca* 300 cal. CE. Minimal impact on the forest composition was detected, but evidence for grass pollen (Poaceae) would likely represent the opening of the landscape for the cultivation of maize. During the Early and Late Classic (300-750 CE), archaeological evidence for increasing activities along the coast of Ambergris Caye has been identified, with the diets of the inhabitants from San Juan and Chac Balam being largely marine-based (Guderjan, 1995; Parker, 2011). From our record, slight increases in forest taxa abundances and declining abundances of openness and disturbance indicators suggest a closure in the forest. The synchronicity between the archaeological evidence for increasing marine-based subsistence and this evidence for increasing forest abundances represents decreasing use of the dry forest ecoregion by island inhabitants.

During the Postclassic, the abandonment of coastal settlements on the island saw increased activity in the interior of the island, with archaeological evidence for occupation at sites such as Basil Jones and San Pedro (Guderjan, 1995; Stemp, Graham and Goulet, 2011; Stemp and Graham, 2016). This increasing activity towards the interior of the island is hypothesised to have influenced subsistence strategies on the island, whereby terrestrial

environments were increasingly used (Guderjan, 1995). The Basil Jones palaeoecological record shows evidence for declining forest taxa abundances (Moraceae/Urticaceae), increases in disturbance and openness indicator taxa (*Mimosa*, Poaceae) and increasing fire activity occurring synchronously with the identification of maize pollen during the Postclassic (~1200 CE). This is identified as the largest period of ecological change associated with land-use and provides the first empirical evidence for shifting subsistence strategies during the Postclassic period.

4:5:2 Establishment of cultivation at Basil Jones

Archaeologists have previously argued that island cultivation on Ambergris Caye was not possible for early inhabitants, until the Postclassic, due to the dominance of mangrove ecosystems throughout the island (Williams, White and Longstaffe, 2009). The environments that support the seasonally dry tropical forests in the north of the island, however, would have provided suitable conditions for early cultivation due to the fertile soils associated with the ecoregion (Gosling *et al.*, 2009). The identification of *Zea mays* pollen in the Basil Jones core dating to around 2900 BCE upturns this long-held assumption and indicates that the earliest cultivation on the island occurred in close proximity to the sinkhole, due to the short transportation associated with the dispersal of *Zea mays* pollen (Lane, Cummings and Clark, 2010)

Early cultivation strategies at Basil Jones are indicated by the identification of *Zea mays* (*ca* 2900 BCE) pollen alongside three high magnitude peaks in the fire record recorded between *ca* 3100-2900 BCE. It is interpreted that these peaks as evidence for early *milpa* agriculture. *Milpa* agriculture is a land-use strategy that uses fire and natural forest succession to traditionally allow for periods of cultivation and forest recovery (Kleinman, Pimentel and Bryant, 1995) and is known to have been a feature of ancient Maya agricultural systems (Rue, 1987; Nigh and Diemont, 2013). Archaeological interpretations for the settlement of Ambergris Caye is suggested to have occurred between *ca* 600-300 BCE (Graham *et al.*, 2017). The findings at Basil Jones suggests a longer history of landscape modification than previously identified. This disparity is a feature of research examining human-environmental interactions in the Maya Lowlands, as the onset of cultivation usually precedes evidence for permanent settlements by hundreds to thousands of years (Pohl *et al.*, 1996; Wahl *et al.*, 2006; Rushton, Metcalfe and Whitney, 2012).

Evidence for agricultural activities on Ambergris Caye closely mirrors its establishment on the mainland. In Belize, which is hypothesised to have initiated by 3000 BCE (Pohl *et al.*,

1996), and in the broader Yucatan Peninsula by 1500 BCE (Carrillo-Bastos *et al.*, 2010) and Guatemala by 2600 BCE (Wahl *et al.*, 2016). Dating early agriculture on Ambergris Caye is important for understanding the wider dynamics between inland and coastal sites throughout the Preclassic to Postclassic periods. With the establishment of agriculture closely aligned to mainland activities, these results highlight the wider influence of mainland activities on the island, establishing evidence for earlier access to the island. A waterway located on the north of Ambergris Caye, the Bacalar Chico Canal, has been hypothesised to be artificially constructed by the ancient Maya to facilitate water-based transportation from the mainland to the eastern coast of the island (Guderjan, 1995) but this hypothesis remains untested. This waterway could be a suitable candidate for how inhabitants first reached the island, with the short distances between the island and the mainland, easily navigable through this passageway. The finding of cultivation by 2800 BCE provides a temporal baseline for understanding how inhabitants accessed the island and until further questions are addressed, the method of access cannot be determined

4:5:3 Dynamic relationship between mainland activities and island activities

The land-use strategies of the ancient Maya on Ambergris Caye cannot be interpreted in isolation to activities on the mainland of Belize. Throughout the history of occupation across the region, the establishment of coastal mainland centres have been linked to have a direct influence on island inhabitants (Guderjan, 1995; Rathje and Sabloff, 2010; Cucina, 2015; Graham *et al.*, 2017). Most of these interactions have been interpreted through the lens of broader growth and decline of sophisticated maritime trade networks (Graham, 1989; McKillop, 2005), with island populations growing in accordance with these mainland coastal centres (Guderjan, 1995; Rathje and Sabloff, 2010; Graham *et al.*, 2017). The palaeoecological record identifies a close synchronicity between these mainland activities and landscape management at Basil Jones. Whilst fire has been previously been discussed as a potential natural feature in seasonally dry tropical forests (Correa-Metrio *et al*., 2012), the dominance of wetland ecosystems throughout the island, coupled with evidence for cultivation, indicates that the fires on Ambergris Caye were likely to have been anthropogenic in origin.

The Preclassic abandonment period (*ca* 250 CE) is associated with a period of social destabilisation, closely chronologically linked with a multi-centennial scale drought (Webster *et al.*, 2007; Medina-Elizalde *et al.*, 2016). This destabilisation was not homogenous throughout the mainland of the Maya Lowlands, as coastal mainland sites

such as Colha and Moho Cay became increasingly important (McKillop, 2010). These centres were likely responsible for managing the trade networks developed along the Caribbean coast, exchanging commodities such as salt and obsidian (McKillop, 2010). On Ambergris Caye, evidence for long-distance exchange is apparent at Marco Gonzalez by ~200 CE (Graham *et al.*, 2017) as ceramics from Yalamha and Laguna de Cayo Francesca indicate Early Classic activities were prominent on Ambergris Caye (Guderjan, 1995). From the Basil Jones palaeoecological record, we identified a period of cultivation by *ca* 300 CE (1 σ 125-450 CE), which is closely associated with the growth of mainland activities and active trading at Marco Gonzalez. Increased variability in the goods traded into Marco Gonzalez has been hypothesised to have occurred during this period (Graham *et al.*, 2017). The identification of macrofossil remains of maize cupules dating between 1-250 CE has been interpreted as evidence for the trading of crops between the mainland and Marco Gonzalez (Graham *et al.*, 2017). The evidence for cultivation at Basil Jones during this period has led to the interpretation that this macrofossil maize remain was sourced from the northern dry forest region of the island and not evidence for trading between the island and the mainland.

The next synchronised event linking mainland dynamics to island land-use can be detected from the re-appearance of *Zea mays* during the Postclassic (*ca* 1200 CE) (Figure 4.3). Following the collapse of the Classic Maya political system and depopulation of some lowland centres (*ca* 750-1100 CE), the Postclassic period saw the re-organisation of populations in settlements along the coast and near water bodies (Miller, 1985; Rushton, Metcalfe and Whitney, 2012; Cucina, 2015), with inhabitants of Ambergris Caye reorganised towards the island interior. This response saw the refocusing of subsistence strategies towards the terrestrial ecosystems on the inland of the island as populations grew at sites such as Basil Jones and San Pedro (Guderjan, 1995). The palaeoecological evidence from this study provides the first empirical results to support the hypothesis of increased use of terrestrial ecosystems on Ambergris Caye during the Postclassic. Whilst this record supports this argument, the evidence also shows extended periods of island land-use throughout the entire Preclassic to Postclassic sequence. Archaeological evidence for abandonment during the Preclassic and Postclassic periods correlate closely with evidence for regional drying from Belizean speleothems (Webster, 2007; Kennett, *et al.*, 2012). These links between land-use and climate aridity broaden our understanding of how landscapes on islands were used to a wider extent than previously thought. Along with showing a strong association between mainland and island activity, these findings also

indicate some degree of resource management by the lower density populations of the ancient Maya on Ambergris Caye. With archaeological evidence indicating high-marine based diets and the palaeoecological evidence presented here showing terrestrial cultivation, it is hypothesised that the coastal communities benefited from the diverse resources available, which potentially mitigated the influence of mainland climate and social instability.

4:6 Conclusions

This chapter presents the first palaeoecological investigation into ancient Maya land-use strategies on an island site in the Maya Lowlands. The record from Ambergris Caye provides important information regarding how these lower density populations interacted with the dry forest ecosystem on the island and how it related to the wider social dynamics of mainland instability. The dominant dry forest ecosystem likely defined where communities first settled on the island, with maize cultivated by 2900 BCE. The synchronicity between periods of cultivation in the northern dry forest and consumption of maize in the mangrove-dominated south may suggest internal resource redistribution and local trade networks. Previously, it was thought that the use of the dry forest ecoregion was limited to the Postclassic. However, evidence from this study expands this narrative to show that the dry forest ecoregion was used for more than two millennia associated with the rise and fall of Classic and Postclassic ancient Maya settlements. Despite these findings, a clear relationship between terrestrial and marine-based economies remains under-studied. Local factors, such as climate change and growing trade networks, likely drove which ecoregions were prioritised throughout time. The Basil Jones results provide an important chronological baseline for when cultivation took place, opening up areas of future research to compare evidence for terrestrial versus marine-based subsistence. Finally, the palaeoecological record at Basil Jones shows a strong relationship between patterns of land-use and periods of socio-political instability on the mainland. It's hypothesised that during periods of mainland migration towards the coast, the landscapes across the island of Ambergris Caye were increasingly cultivated. This relationship may indicate that the island was used as a refuge during periods of social or climatic stress, in which the availability of diverse and locally available resources drove mainland communities to these environments.

4:7 Authors contributions and acknowledgements

This chapter was written by Adam Bermingham who undertook all the pollen/charcoal preparation, counting and analysis. Principal supervisor Dr Bronwen Whitney collected the core for this thesis in the summer of 2016, before the start of the project. Dr Julie Hoggarth aided with the archaeological interpretations.

Chapter 5 A long-term record of ancient Maya land-use in the Laguna Esmeralda watershed (Quintana Roo)

5:1: Overview

This chapter examines the palaeoecological record from the lake known as Laguna Esmeralda, located in the northern Yucatan Peninsula state known as Quintana Roo, to assess the impact of smaller ancient Maya mainland communities on the seasonally dry tropical forest. A combination of pollen and charcoal proxies were analysed in conjunction with a CHARanalysis methodology to construct past fire regimes in the locality. This record reveals varying scales of impact associated with maize agriculture and provides a new chronological baseline for the onset of cultivation in the northern lowlands. During periods of drought, contrasting scales forest impact are associated with ancient Maya cultivation, providing new insights into the impact of climate change on subsistence strategies such as shifting cultivation patterns between two adjacent lake systems.

5:2 Introduction

The complexity of human-environmental interactions during periods of climate change is highlighted in research examining ancient Maya land-use (Whitmore *et al.*, 1996; Diemont *et al.*, 2011; Aragón-Moreno, Islebe and Torrescano-valle, 2012; Turner and Sabloff, 2012). Palaeoclimate records have identified periods of climate drought throughout the Maya Lowlands that temporally correlate with archaeological evidence for periods of social instability (Hodell, 2007; Webster, 2007; Kennett *et al.*, 2012), which ultimately culminated with a link between high-magnitude drought events and the *collapse* of the Classic Maya civilisation between *ca* 750-1100 CE. The environmental deterministic hypothesis for the decline of the Classic Maya has attributed palaeoecological evidence for deforestation associated with ancient Maya land-use (Rosenmeier *et al.*, 2002; Dull, 2007; Lozano-García *et al.*, 2010; McNeil, 2012) as evidence for long-term environmental exploitation (Shaw, 2003; Diamond, 2005). In this narrative, the ancient Maya continuously degraded the environment, reducing the storage capacity of the soil and in-turn increasing their vulnerability to drought episodes (Shaw, 2003; Diamond, 2005). The major centre of Coba, located in the eastern Yucatan Peninsula, highlights this phase of deforestation in association with land-use strategies as a 60% reduction in arboreal pollen is recorded during the Preclassic period (Leyden, 2002). From a land-use perspective, the number of records representing the entire peninsula is limited (Leyden, 2002; Carrillo-Bastos *et al.*, 2010; Aragón-Moreno *et al.*, 2012; Torrescano-Valle *et al.*, 2015). Whilst the Coba record identifies one extreme form of ancient Maya land-use, from an urban centre perspective, the understanding of land-use from lower-density settlements remains limited.

The Yucatan Peninsula (covering the political districts of Quintana Roo, Yucatan and Campeche, along with northern Belize and Guatemala) (Figure 5.1), shows extensive archaeological evidence for ancient Maya settlement. A combination of high-density urban locations such as Chichen Itza and Coba (Leyden, 2002; Folan *et al.*, 2009; Hoggarth *et al.*, 2016) and lower density settlements (Villamil, 2005, 2009; Villamil and Sherman, 2017) are located throughout the peninsula, providing important context for this examination. Combined with the aforementioned records for ancient Maya land-use, the Yucatan Peninsula contains numerous high-resolution palaeoclimate records showing evidence for the drought events identified as an important driver of periods of abandonment in the region (Hodell *et al.*, 2005; Hodell, Brenner and Curtis, 2007; Carrillo-Bastos *et al.*, 2010; Brenner *et al.*, 2018). Research investigating the complex processes between ancient Maya

settlement, climate change and land-use strategies primarily focus on the large urban regions in the Yucatan Peninsula (Leyden, 2002), with little attention paid to how climate change impacted the land-use strategies of low-density communities. This research aims to address this site bias by examining a lake that shows no evidence for high-density populations, Laguna Esmeralda. Laguna Esmeralda is located close to Lake Chichancanab, a lake well-studied from a palaeoclimate perspective (Hodell, Curtis and Brenner, 1995; Hodell *et al.*, 2005; Evans *et al.*, 2018). Research has suggested that the two lakes were connected during times of high water (Hodell *et al.*, 2005). If these lakes were connected in the past, it can be assumed that the Lake Chichancanab record provides a local reconstruction of hydrological conditions for both watersheds and thus can provide a high-resolution, local, reconstruction of climate.

5:3 Methods and study site summary

For this chapter, all fieldwork, preparation techniques, statistical analysis and radiocarbon dating methodology are extensively discussed in Chapter 3. Pollen preparation followed standard procedure (Faegri and Iversen, 1989), with an additional sieving employed to isolate large cultigen pollen grains (Whitney *et al.*, 2012). Charcoal sampling and counting were split between the author and colleagues from Nottingham University, with 15 samples swapped between analysts to ensure consistency in the counting. An analysis of the raw charcoal data through the CHARanalysis protocol saw samples smoothed and fire frequency analysed at a 700-year time window to maximise the goodness of fit (GOF) and signal to noise (SNI). Zonation of the pollen required a transformation of the raw pollen data via square root transformation and was then zoned via the optimal sum of squares (Bennett, 1996). Stratigraphy diagrams were plotted in the C2 software (Juggins, 2007) (Chapter 3: section 3:11:2).

The dominant ecosystem that covers Laguna Esmeralda is seasonally dry tropical forest, *Bursera simaruba*, *Brosimum alicastrum* and *Gymnopodium floribundum* important components (White and Hood, 2004; Urquiza-Haas, Dolman and Peres, 2007; Carrillo-Bastos *et al.*, 2010). The archaeological context shows no permanent settlements in the vicinity, with the ancient Maya centre of Yo'okop the closest archaeological site to the lake (~20km). Further archaeological and environmental descriptions are found in Chapter 3 (section 3).

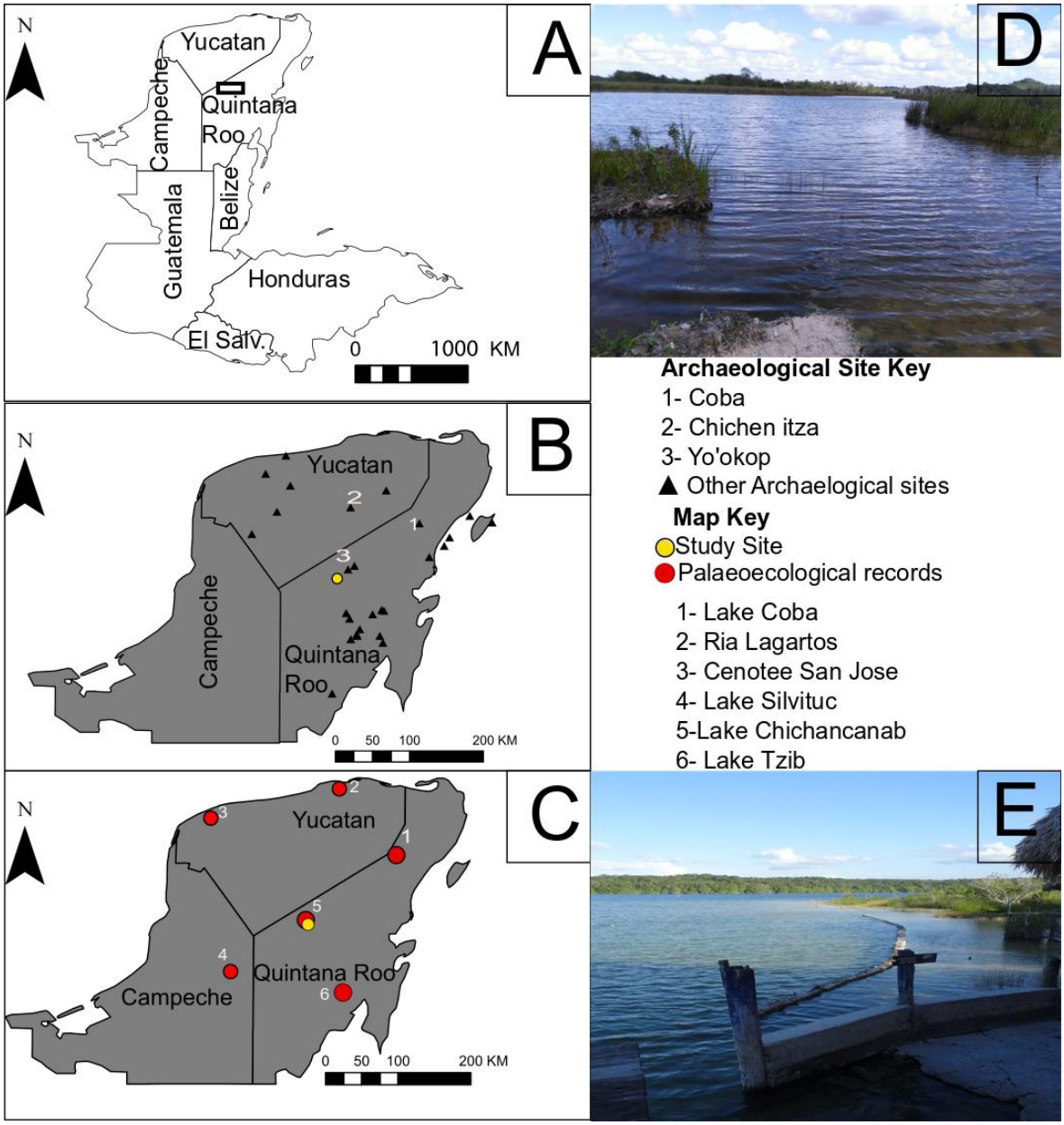

Figure 5.1 Map highlighting the location of the study sites within (A) northern-Central American continent. (B) Archaeological context with sites 1-2 important political capitals during the ancient Maya era and Yo'okop the closest archaeological site to the Laguna Esmeralda watershed. (C) Map highlighting the palaeoenvironmental investigations completed in the region. (1) Lake Coba (Leyden, 2002);(2) Ria Lagartos (Aragón-Moreno, Islebe and Torrescano-valle, 2012)*; (3) Cenotee San Jose (Leyden, 2002);(4) Lake Silvituc* (Torrescano-Valle and Islebe, 2015)*; (5) Lake Chichancanab (Leyden, 2002). (D) Digital photograph of Laguna Esmeralda with coring location in the distance. (E) Digital photograph of Lake Chichancanab both obtained in January 2020.*

Table 5.1 Table of ecological groupings, palaeoecological interpretations and ecological association (SDTF = seasonally dry tropical forest) for taxa identified in the Basil Jones core. Palaeoecological interpretations are based off a combination of the PCA diagram (Appendix A) and also the ecological and vegetation description highlighted in Chapter 2

Taxa identified	**Vegetation grouping in the pollen diagram**	**Paleoecological interpretation**	**Ecological association**
Brosimum	Trees and Shrubs	Primary forest/potential anthropogenic	SDTF
Ficus	Trees and Shrubs	Primary Forest	SDTF
Maclura	Trees and Shrubs	Primary Forest	SDTF
Solanaceae	Trees and Shrubs	Primary forest/potential human indicator	SDTF but also present in other ecosystem types
Anacardiaceae	Trees and Shrubs	Forest vegetation	SDTF
Betulaceae	Trees and Shrubs	Forest vegetation	SDTF
Quercus	Trees and Shrubs	Forest vegetation	Potentially transported from savannah vegetation
Pinus	Trees and Shrubs	Forest vegetation	Potentially transported from savannah vegetation

Acalypha	Trees and Shrubs	Forest vegetation	SDTF
Guazuma	Trees and Shrubs	Forest vegetation	SDTF
Alnus	Trees and Shrubs	Forest vegetation	Potential long-distance transported from highland regions
Boraginaceae	Trees and Shrubs	Forest vegetation/potential shrubs	SDTF
Metopium Brownei	Trees and Shrubs	Forest vegetation	SDTF
Piscidia	Trees and Shrubs	Forest vegetation	SDTF
Acacia	Trees and Shrubs	Forest vegetation/potential shrubs	SDTF
Fabaceae	Trees and Shrubs	Forest vegetation	Present in a range of ecosystem types
Combretaceae/Melastomataceae	Trees and shrubs	potential coloniser vegetation	SDTF but also present in savannah vegetation and wetland ecosystems
Sapium	Trees and Shrubs	Forest vegetation	SDTF
Celtis	Trees and Shrubs	Secondary taxa/early coloniser	SDTF

Myrica	Trees and shrubs	Secondary taxa/early coloniser	SDTF
Gymnopodium	Trees and shrubs	Shrub vegetation	SDTF
Bursera simaruba	Trees and Shrubs	Shrub species, Early coloniser species	SDTF
Mimosa	Trees and Shrubs	Disturbance indicator	SDTF
Poaceae	Herbs	Disturbance/openness indicator	Grasses found in a range of disturbed environments
Asteraceae	Herbs	Disturbance/openness indicator	found in a range of disturbed environments
Chenopodiaceae/Amarantaceae	Herbs	Disturbance/openness indicator	found in a range of disturbed environments
Cyperaceae	Herbs	Disturbance/openness indictor	found in a range of disturbed environments
Avicennia Germinans	Mangrove	Mangrove indicator	Likely long-distance transportation
Sagittaria	Aquatic vegetation	Local aquatics	Potentially linked to lake hydrology
Typha	Aquatic vegetation	Aquatic indicator	Potentially linked to lake hydrology

5:4 Results

5:4:1 Stratigraphy

Field descriptions describe the core as dark in colour, indicative of organic material, with various degrees of lithological banding. The final two drives (below 150cm), consisted of less variation in the colouring with faint banding.

5:4:2 Chronology and age modelling

Samples for radiocarbon dating were sent to the NERC radiocarbon facility in East Kilbride (allocation number 2057.0417) (Table 5.2). Selection of material was previously discussed in Chapter 3 (Section 3:7:3). The radiocarbon age model was constructed using the clam package in R (Blaauw, 2010b) and calibrated using the INTCAL13 radiocarbon curve (Reimer *et al.*, 2013). Dating of individual horizons was completed through interpolation (Figure 5.2). Due to the dating of bulk sediments, a reservoir influence was included in the age model construction. Assuming that the modern sample for dating would be the date of coring (2016), the estimated hardwater effect was calculated by the distance between the ^{14}C dates and the modern assumed date. Based on these assumptions an estimation of 330 years was calculated for the Laguna Esmeralda hardwater effect. For the remainder of the ^{14}C dates, the reservoir effect was accounted for, making the calibrated ^{14}C ranges younger than the original ^{14}C dates (Table 5.2).

Table 5.2 Materials sent for radiocarbon dating to the NERC institute in Glasgow. Calibrated ages obtained from the "clam" age model

Publication Code	**Study Site**	**Sample Depth (cm)**	**Material Selected**	**δ^{13}Cvpd per (ml)**	**Radiocarbon age (yr. BP ±1 σ)**	**Calibrated radiocarbon age (yr. BP ±1 σ)**	**Calibrated radiocarbon age (mean probability)**
SUERC-75747	Laguna Esmeralda	0-3	Bulk sediment picked of shells	-27	264 ± 35	(-)66 – (-)64	-65
SUERC-75751	Laguna Esmeralda	46.25	Bulk sediment picked of shells	-23.5	1630 ± 37	1144-1262	1207
SUERC-75752	Laguna Esmeralda	94.75	Bulk sediment picked of shells	-25.9	2083 ± 37	1625-1836	1715
SUERC-75753	Laguna Esmeralda	144.25	Bulk sediment picked of shells	-20.8	4101 ± 37	4024-4278	4159
SUERC-82294	Laguna Esmeralda	387	Bulk sediment picked of shells	-21.0	6127 ± 37	6500-6684	6590

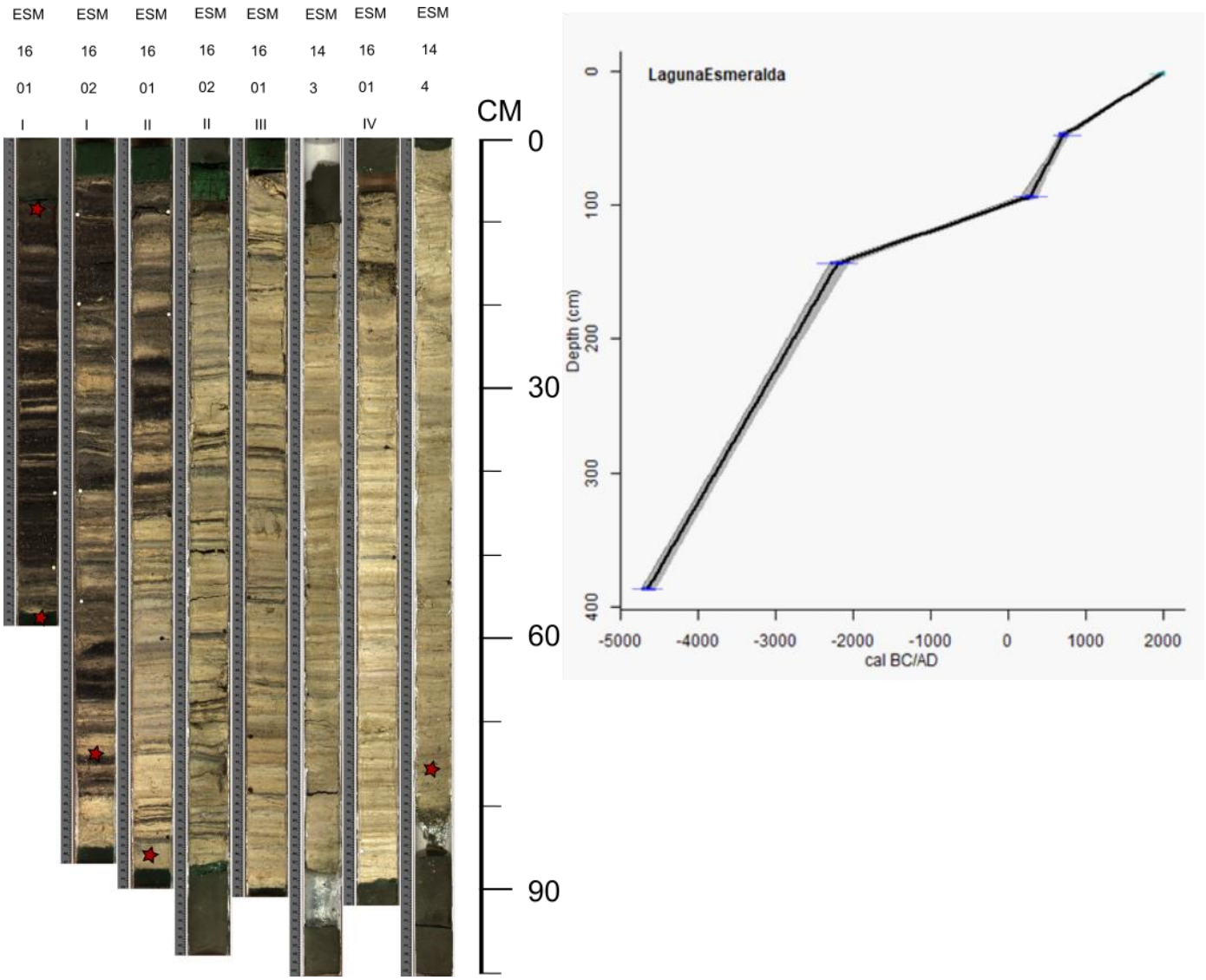

Figure 5.2 Age depth calibration model using the IntCal13 calibration curve. Ages are produced to 2-sigma uncertainty ranges (95th percentile). Reservoir effect was input as 330 years to account for potential offsets associated with the dating of bulk sediments Results are presented in cal. BC/AD

5:4:3 Palaeoecological analysis

Zonation of the microfossil pollen record produced three statistically significant zones. Results have been split between most abundant taxa (Figure 5.3) and the remainder of pollen abundances contributing to the assemblage (Figure 5.4).Moraceae/Urticaceae (B) are the combined totals of members of the Moraceae/Urticaceae family (*Ficus*, Moraceae/Urticaceae (B), with *Brosimum* and *Maclura* plotted individually due to their importance to the dry forest assemblage. For the description of the results in this chapter, Moraceae/Urticaceae will be the summed total of *Ficus*, Moraceae/Urticaceae (*other)*. Results of the CharAnalysis reconstruction are presented with the pollen zones (LE1-LE3). Key results described are peak events that passed the 95% threshold (including magnitude) and fire frequency per 700 years (Figure 5.6). Fire frequency per 700 years records the number of peaks recorded across the moving time window.

5:4:3:1 LES-3 344- 187cm 6.17-4.59 kyr cal. BP/ 4220-2640 BCE (14 samples)

This zone captures the first appearance of *Zea mays* in the record at *ca* 3535 BCE (3600-3460 BCE 2-σ calibrated range). Within this zone forest pollen dominates, with Moraceae/Urticaceae (B), *Brosimum* and *Maclura* dominating the assemblage. Charcoal concentrations are low, as are disturbance (Poaceae, Asteraceae) and smaller tree abundances (*Celtis*, *Bursera*).

Between *ca* 4200-2800 BCE, Moraceae/Urticaceae abundances increase (28-59%) and then decreased between 2700-2600 BCE by 35%. From the same family, but removed from the combined abundances, *Brosimum* increases between 4200-3500 BCE (5-18%), before decreasing for the next 500 years (minimum recorded abundance = 4%). From *ca* 3000 BCE to the end of the zone, abundances vary from 6-18%. Secondary forest taxa *Bursera* (9%) and *Celtis* (2%) are recorded throughout the zone. Low abundances of Anacardiaceae (undif) (<1%) and Cyperaceae (<3%) are also recorded. Asteraceae shows similar low percentages (<3%) bar a peak between 3500-3400 BCE (5%). Poaceae varies, peaking at the base sample (15%) and then ranging from 1-11% throughout. Aquatic taxa *Typha* appears inconsistently and in low abundances (<1%). Mean assemblage values of other taxa include Trema (3%), Combretaceae/Melastomataceae (2%), *Metopium brownei* (3%), Fabaceae (2%), *Mimosa* (3%), and *Acalypha* (3%). Two fire peaks are recorded in LES-3, with neither greater then $15cm^2yr^{-1}$. Fire frequency decreases from 2 to <1 fires per 700 years, increasing to 2.5 at the top of the zone.

5:4:3:2 LES-2 187-101cm 4.28-2.2 kyr cal. BP/ 2640-116 BCE (7 samples)

This zone sees the highest occurrences of *Zea mays* preservation in the record with its repeated appearance between *ca* 2200-1400 BCE. Similar to the last zone, forest pollen is dominating the assemblage, with little of a shift in ecology. Smaller trees such as *Bursera* and disturbance indicator Asteraceae, reach their highest abundances in this zone, indicating some degree of disturbance, potentially a shift from closed forest vegetation to a more open landscape.

Forest taxa Moraceae/Urticaceae gradually increases in abundances throughout the zone (21-32%), before the abundances are halved (15%) in the final sample of the zone at 200 BCE. This reduction in Moraceae/Urticaceae was shown to be influenced by the closed sum effect, as absolute concentrations show no little changes during this period (Figure 5.5). *Brosimum* remains low at the beginning of the zone (~2%) and then increases (2-16%) for the remainder, reaching its peak at 200 BCE. At the beginning of the zone, *Bursera* abundances are high between 2400-2300 BCE and then declines throughout the remainder of the zone, with a low abundance of 2% recorded at 1300 BCE. *Celtis* remains in low abundances until the final sample where it reaches a record peak of 10%. Anacardiaceae decreases continuously following a peak of 10% at 2300 BCE and recording <1% abundances at the end of the zone. Poaceae decreases in abundances ranging from 3-10% throughout the zone. Asteraceae fluctuates between high and low abundances throughout, with 11% and 25% reached at 2100 and 700 BCE, respectively. Cyperaceae abundances remain relatively consistent throughout the zone (~4%) and then decreases for the final two samples (1% minimum). *Typha* appears sporadically low abundances (<1%). Mean abundances of important taxa, such as *Metopium brownei* (3%), *Mimosa* (2%), Fabaceae (3%) and *Pinus* (2%) also contribute to the zone.

Two fire peaks are recorded in this zone but are low in magnitude (11.7cm^{2}yr^{-1} and 0.14cm ^{2}yr^{-1}). Fire frequency is approximately 2 fires per 700 years between 2600-2200 BCE and then gradually decreases to 0 at the end of the zone.

5:4:3:3 LES-3 101-surface 1.77 kyr cal. BP-modern (180-2016 cal. CE) (14 samples)

In the LES-3 zone, *Zea mays* are recorded at 1030 and 1850 CE. Moraceae/Urticaceae gradual increases in abundance until a reduction is recorded between *ca* 850-950 CE (62-17%). Forest abundances remain particularly high but are recording a shift to lower abundance in response to increasing abundances of smaller trees such as *Celtis*. Poaceae record its highest abundances in the record indicating, similar to the previous zone, a more open landscape in accordance with the appearance of cultivation pollen.

The remainder of the zone sees gradual increases once more, until the final sample where its record lowest abundance is recorded (8%). *Brosimum* also varies with peaks recorded at *ca* 600 CE (22%) and 400 CE (14%), whilst appearing in relatively low values between *ca* 1000-1800 CE (9-13%). *Bursera* gradually decreases from the base of the zone, before it reaches peaks at 750 CE (10%). For the remainder of the zone, it remains variable in abundances, recording 12% abundances for the final sample of the zone. *Celtis* abundances show similar inconsistencies, ranging between 1-10% throughout the zone with its maximum recorded at 500 CE. Anacardiaceae (*undiff*) has a record high peak for the first sample in the zone, 150 CE (17%) and the decreases rapidly throughout the zone, ranging between 1-10%. Poaceae records >10% abundances at 600, 750, 850 and 1300 CE. Asteraceae records <3% abundances throughout the entire zone, bar the final sample where it records 13%. Cyperaceae fluctuates inconsistently ranging from 2-8% across the entire zone, with a record high recorded at 900 CE. *Typha*, for the first time in the record, reaches >1% abundances on two occasions (950, 1300 CE). Mean values of other important species include *Trema* (2%), Combretaceae/Melastomataceae (2%) and *Metopium brownei* (4%). Three fire events are recorded in this zone, with the maximum magnitude peak of the record recorded at 490 CE (31.910$cm^{-2}yr^{-1}$). From the beginning of LES-3, fire frequency gradually increases above 1 until the end of the zone where it is above 2 fires per 700 years.

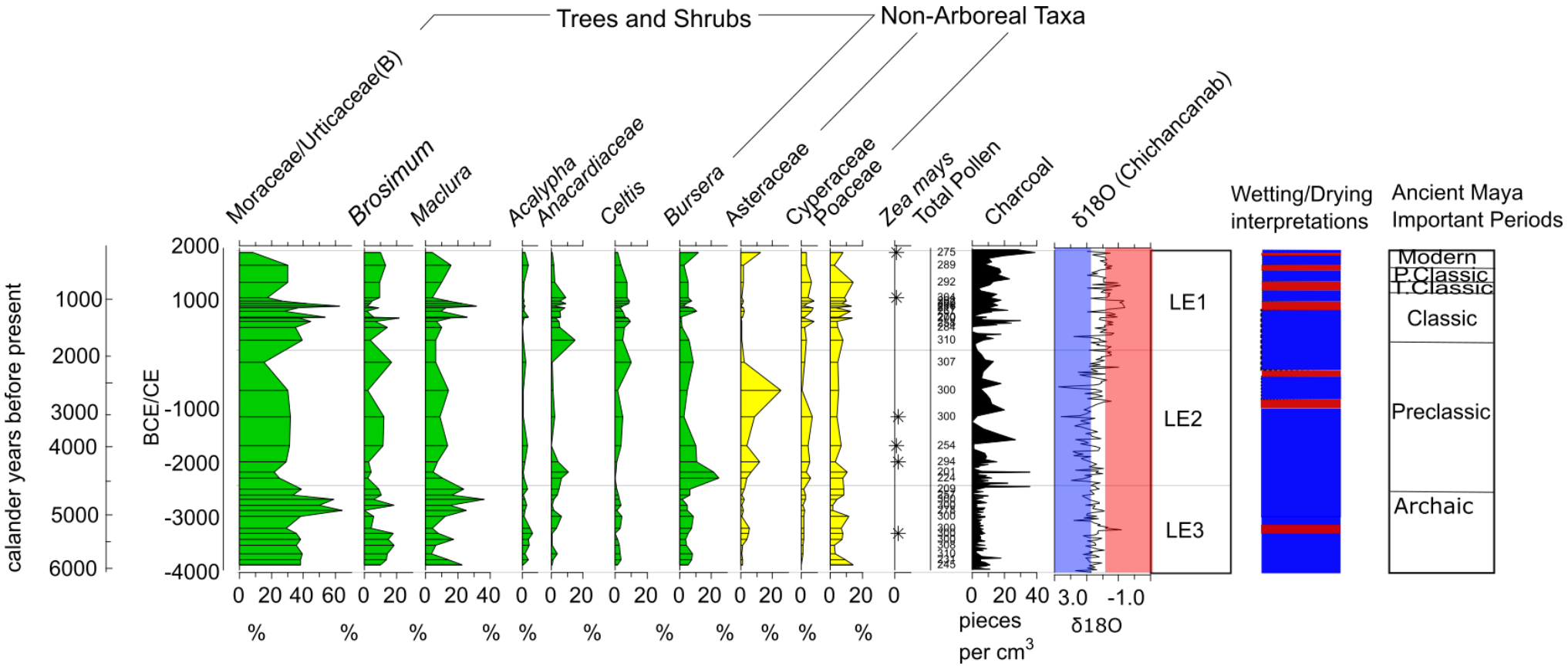

Figure 5.3. Most abundant taxa from the Laguna Esmeralda core (%). Moraceae/Urticaceae (B) = sum of all taxa from the Moraceae/Urticaceae family minus Brosimum abundances. Anacardiaceae represents members of the family, which were not identified as Metopium or Spondias type. Charcoal presented fragments per cm^3. Zea mays (maize) presented as absolute counts. Palaeoclimate records from the adjacent Lake Chichancanab (Hodell et al., 1995) are also given, with coloured bars used to present interpretations of wetting and drying. For archaeological context, important ancient Maya periods are also displayed.

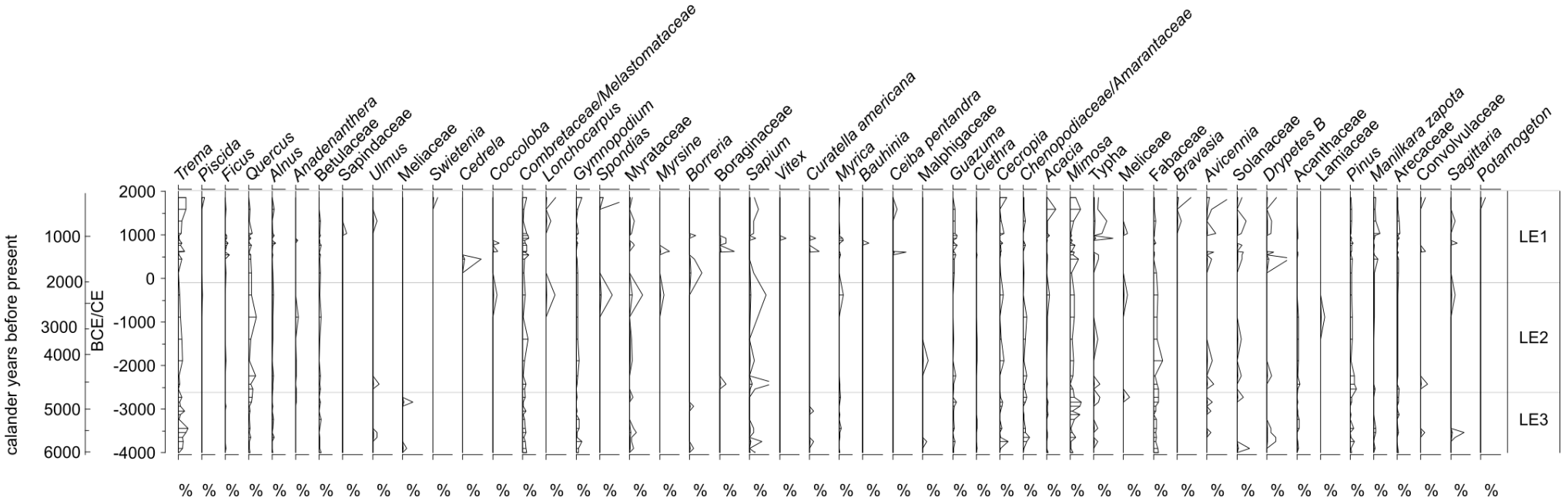

Figure 5.4 Remaining percentage abundances of taxa recorded from the Esmeralda core. Low abundance species were treated with an x10 exaggeration line to improve clarity.

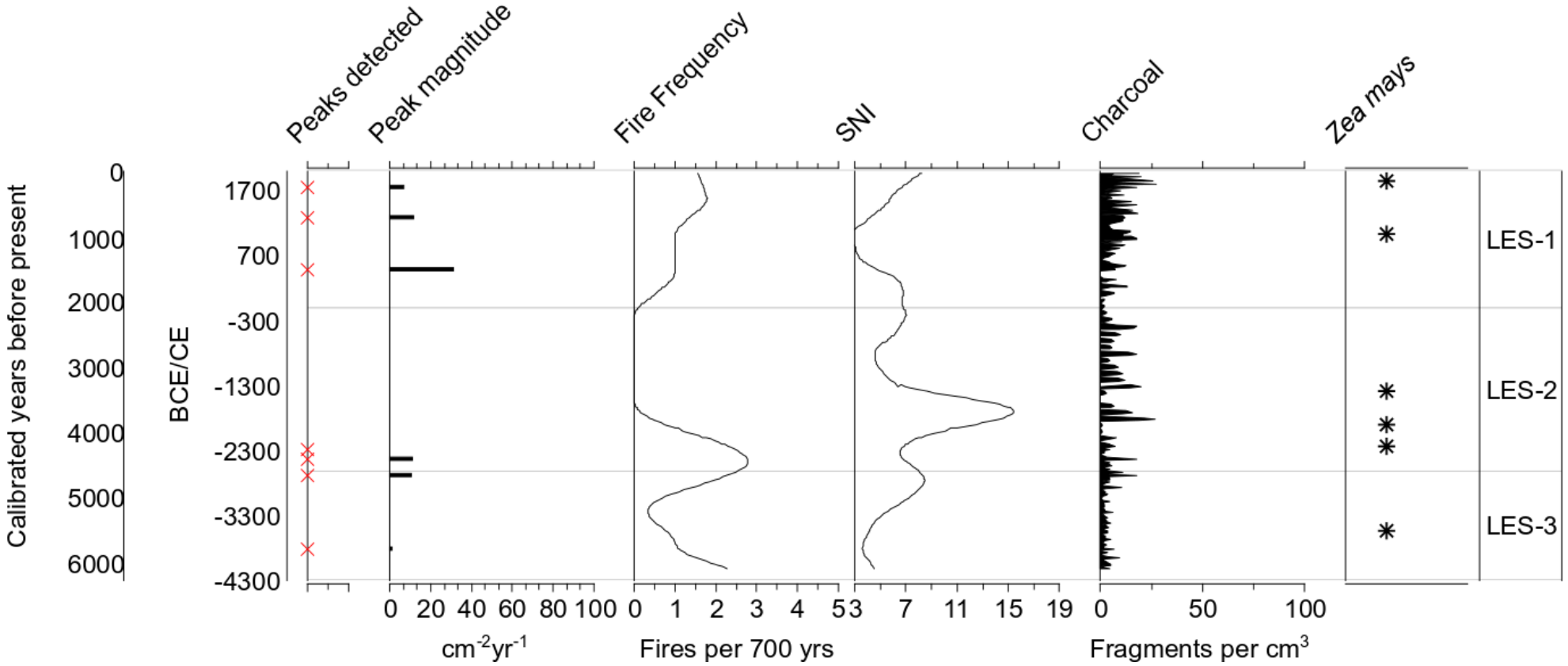

Figure 5.5 Results of the CHARanalysis protocol. Peak magnitude is only shown for significant peaks detected (passed 95% threshold). SNI= Signal to Noise. Fire frequency is recorded per 700 years. Charcoal is the record before the analysis. Zea mays added for the context of ancient Maya land-use

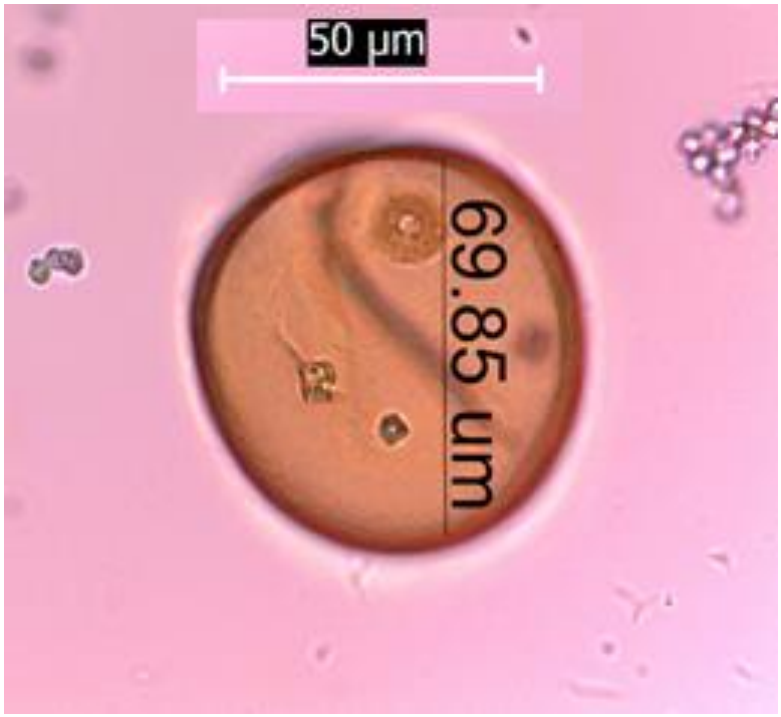

Figure 5.6 Images of Zea mays pollen obtained from the Laguna Esmeralda core. Range of radiocarbon dates places this finding between 3600-3450 CE (5.4-5.6 kyr cal. BP).

5:5 Discussion

5:5:1 Ancient Maya land use at Laguna Esmeralda

The palaeoecological record from Laguna Esmeralda reveals over 5500 years of changing land-use associated with the appearance of cultigen pollen and changing variations in arboreal and non-arboreal pollen. The presence of *Zea mays* in the record throughout varying periods are also associated with contrasting degrees of forest cover impact (Archaic/Preclassic = low impact, Terminal Classic = high relative impact on forest cover). Palaeoclimate records from Lake Chichancanab indicate various phases of climate drying associated with two periods of cultivation in the Laguna Esmeralda record, implying a close relationship between increasing use of the surrounding landscape and increasing drought. One possible reason for this increase in *Zea mays* signal during drying periods, is that the crop was cultivated closer to the lake, following lower lake levels in drier periods. With an increasing number of crops located closer to the lake, in drier conditions, the signal of *Zea mays* would be likely amplified and vice versa (wetter conditions would increase lake levels, decreasing the signal of *Zea may*). In this research, the complicated patterns between lake levels and the signal for *Zea mays* cannot be resolved, without additional geochemical proxy verification. For this reason, the appearance of *Zea mays* in the record is interpreted as localised crop land-use. Based on the size of the Laguna Esmeralda basin (~250m in diameter) the palaeoecological record is assumed to reflect local patterns of vegetation change, due to concepts derived from relative source theory (Prentice, 1985; Bunting *et al.*, 2004). This relatively small lake would have an increased likelihood of capturing localised crop land-use then some of the larger lakes around Central America. However, even though the lake is more likely to capture a local signal, numerous process are involved in being able to identify *Zea mays* in a long-term sediment record. Deposition of the grains may have been heavily influenced by local meteorological conditions (wind direction), whilst methodological procedures could have inhibited the preservation of the grains. Therefore, even though the finding of Zea mays is interpreted here as reflective of land-use, the lack of evidence of *Zea mays* in the record does not strictly indicate that land-use did not exist at that period, based on the aforementioned variables.

The low concentrations of charcoal preserved from the lake sediments, and subsequent low number of peaks detected in the analysis of the data (CHARanalysis), shows that the scale

of burning was not large enough to produce high quantities of charcoal. The number of events recorded, along with the magnitude of fire events supports the notion that fire was used as a landscape management tool, but on a lower scale. The low concentrations of charcoal recorded in the record may be linked to the variations in sedimentation recorded from the core. During the two highest periods of sedimentation (*ca* 0-2000 CE and 2500-6000 BCE), fire frequency is also at its highest levels. When sedimentation slows down (*ca* 2500BCE- 0 CE), fire frequency is also low. For future research, higher resolution of sampling would need to be targeted at these lower sedimentation rates, as one sample covers a larger chronological period than in the upper and lower parts of the core.

5:5:1:1 The Archaic (ca 6-4 kyr cal. BP/4000-2000 BCE)

The Laguna Esmeralda record establishes evidence for phases of cultivation at *ca* 3500, 2100 BCE, whilst the results of the CHARanalysis identifies three peak events, with at least one peak closely associated with the appearance of *Zea mays* (*ca* 2200 BCE). Palaeoecological records from Lake Coba has shown a period of forest decline between 4000-2000 BCE but has not been attributed as evidence for anthropogenic forest clearances (Leyden, 2002). Local climate conditions, provided from the Lake Chichancanab record, indicates that a period of climate drying is evident between 3400-3200 BCE with a shift towards wetter conditions is then recorded for the remainder of the Archaic period (Hodell, Curtis and Brenner, 1995). Elsewhere, palaeoecological records from Guatemala indicates minimal forest clearance before 2000 BCE (Anselmetti *et al.*, 2007).

Periods of land-use are closely associated with the presence of *Zea mays* pollen and increasing disturbance/openness indicators (Poaceae, *Cecropia*, Asteraceae, Chenopodiaceae/Amaranthaceae) (Leyden, 2002; Carrillo-Bastos *et al.*, 2010; Mueller *et al.*, 2010; Islebe *et al.*, 2018) with subsequent reductions in forest abundances interpreted as deforestation associated with Maya land-use (Paine and Freter, 1996; Leyden, 2002; Rosenmeier *et al.*, 2002; Dull, 2007; Lozano-García *et al.*, 2010). Presence of *Zea mays* pollen at *ca* 3500 BCE, declining percentages of Moraceae/Urticaceae and increasing percentages of Poaceae and Asteraceae indicate an anthropogenic impact associated with cultivation. Before its appearance, a small magnitude fire peak is recorded, although the temporal differences (~400 years) makes it difficult to determine if it is anthropogenic in origin. Increasing *Bursera* percentage reflect the disturbance, their early colonising nature would reflect openings available on the landscape driven by clearance of vegetation. Evidence for *Zea mays* cultivation then disappears for more than 1000 years, followed by

increasing forest abundances between 3500-2800 BCE. These increasing abundances suggest that ancient Maya land-use declined, allowing for forest recovery as previously shown in records throughout the lowlands (Wahl *et al.*, 2006, 2007; Mueller *et al.*, 2010). Rather than complete abandonment, the landscape was potentially sporadically used to support cultivation during the Archaic, as permanent settlements were not prominent throughout the lowlands (Brown, 1980; Lohse, 2010; Rosenswig *et al.*, 2014).

The lack of surface water in the Yucatan Peninsula, likely made lake systems, such as Laguna Esmeralda, an important location for the first inhabitants to practise cultivation. A continued period of climate aridity from Lake Chichancanab potentially links to this period of abandonment, which is detected through the declining presence of maize in the record (Hodell, 1995; Hodell *et al*., 2005). As previously mentioned, it has been hypothesised that both Laguna Esmeralda and Lake Chichancanab were connected in the past, providing a local climate reconstruction for both catchments. The period of climate aridity indicates that climate pressures cannot be attributed to the forest recover, as increased precipitation has been previously linked to increasing forest abundances (Leyden, 1984). As Moraceae/Urticaceae percentages stabilise towards the end of the Archaic Period, percentage abundances show declines in *Bursera* along with peaks in disturbance taxa Asteraceae. Changes in the Poaceae curve mirror similar changes to openness indicators (such as *Cecropia* and Asteraceae) and therefore has been interpreted to reflect terrestrial vegetation rather than aquatic.

Between 2700-2300 cal. BCE, *Bursera* and *Brosimum* abundances increase three peaks in the fire record, with two (2700,2400 cal/ BCE) relatively high in abundance. Following these key changes, *Zea mays* is recorded at *ca* 2100 cal. BCE. At the onset of this period of cultivation, *Bursera* sharply declines interpreted as a disturbance indicator. The small tree was likely easier managed by the ancient Maya, then the larger forest components, and therefore removed to support small scale cultivation, with the peaks in fire improving the efficiency of this removal. The consistent abundances and percentages of Moraceae/Urticaceae, which declined during the previous period of cultivation during the Archaic, highlights that the main forest taxa were not heavily impacted to support the cultivation

5:5:1:2 The Preclassic (ca 4-1.7 kyr cal. BP/2000 BCE- 200 cal. CE)

The Preclassic period is established throughout palaeoecological records as a period of increased ancient Maya influence, mainly seen through periods of deforestation (Leyden,

2002; Rosenmeier *et al.*, 2002; McNeil, Burney and Burney, 2010; Mueller *et al.*, 2010; Walsh and Prufer, 2014), with soil erosion interpreted as evidence for extensive Maya modification of the landscape (Anselmetti *et al.*, 2007; Carozza *et al.*, 2007; Fleury *et al.*, 2015) along with evidence for increasing growth of maize (Leyden, 2002; Douglas *et al.*, 2015). Palaeoclimate records from Lake Chichancanab indicates a general shift to increasing precipitation throughout the Preclassic in the Yucatan (Hodell, Curtis and Brenner, 1995; Brenner *et al.*, 2002; Hodell *et al.*, 2005; Brenner *et al.*, 2018). The record indicates that cultivation of *Zea mays* was practised during the early parts of the Preclassic (*ca* 2000-1400 BCE), with a decline in Moraceae/Urticaceae percentage abundances also recorded (*ca* 1000 BCE-50 CE).

Following the transition between the Archaic period and Preclassic period, maize cultivation is found at 1800 BCE at Laguna Esmeralda. Increasing Asteraceae abundances following 1800 BCE indicates disturbances associated with cultivation, although the consistent abundances of Moraceae/Urticaceae and increasing in *Brosimum* indicate that the major taxa of the seasonally dry tropical forest were not impacted by this period of cultivation. Similar to the period of cultivation discussed at 2100 BCE, declining abundances of *Bursera* indicate that the smaller tree was removed to efficiently cultivate the landscape. The disappearance of maize from the record 1200-700 BCE indicates that our record captures no signal for cultivation. Forest abundances remain relatively stable with abundances of *Bursera* and *Brosimum* decreasing, interpreted as an anthropogenic impact on the forest, despite no evidence for cultivation. This is linked to *Bursera* being a quick coloniser species (occupying the cleared landscape) and *Brosimum* (an economically important species used for food and shade) being part of the primary forest (Islebe *et al.*, 2006; Mueller *et al.* 2010). The declining forest abundances may reflect natural impacts to forest declines, such as storms or natural variation in abundances, or reflect continued management by the ancient Maya community. With no evidence for cultivation, the declining forest abundances cannot be attributed to an artefact of landscape management for subsistence. Potentially, these forms of land-use moved away from the Laguna Esmeralda catchment, explaining the lack of evidence for cultivation during this period. Laguna Esmeralda may have continued to have been an important water resource for the ancient Maya communities, with the declining abundances of *Bursera* and *Brosimum* reflecting forest impact associated with the management of a resource.

5:5:1:3 The Classic ca 1.7-0.9 kyr BP (200-1000 cal. CE)

Following the Preclassic period, the development of Classic Maya society saw the establishment of major political centres in the northern Maya Lowlands, with Chunchucmil and Yaxuna growing in prominence during the early Classic (Stanton, 2012) with Coba and Chichen Itza expanding during the Late Classic (Folan *et al.*, 2009; Hoggarth *et al.*, 2016). Records from the northern Yucatan indicate increasing clearance events (Leyden, 2002; Aragón-Moreno, Islebe and Torrescano-valle, 2012), with Lake Silvituc and Chichancanab also indicating increasing clearance (Leyden, 2002; Torrescano-Valle and Islebe, 2015). Impact at Lake Coba (Leyden, 2002) remains intensive, as Lamanai in Belize shows increasing clearance associated with land-use (Rushton, Metcalfe and Whitney, 2012). Climate conditions are in a generally dry state, with little variation according to the Chichancanab record until 800 CE (Hodell *et al*., 1995; Hodell *et al.*, 2005), indicating the transition to the Terminal Classic period. The record at Laguna Esmeralda shows no evidence for cultivation but does indicate irregularities in forest abundances and one high magnitude fire event (*ca* 500 CE).

Whilst the Esmeralda record shows no evidence for Maya cultivation throughout the Classic Period, evidence for *Zea mays* pollen is established at the adjacent Lake Chichancanab (Leyden, 2002). This establishes the chronological baseline (earliest evidence) for activities around Lake Chichancanab, as no previous evidence exists for cultivation from the record (Leyden, 2002). This indication of land-use at Lake Chichancanab potentially indicates a shifting cultivation strategy, whereby practices were refocused towards Lake Chichancanab and away from Laguna Esmeralda. Potentially, the larger catchment of Lake Chichancanab provided more resources to support larger populations, compared to the smaller catchment of Laguna Esmeralda. The high-magnitude fire event may be anthropogenic in origin, due to active land-use in a nearby lake basin, although natural drivers of these fires (such as storms or lightning triggered events) cannot be discounted (Pulla *et al.*, 2015) as they have been shown to have occurred before human arrival in Central America (Correa-Metrio *et al*., 2012). In this ecological setting, fire frequency is expected to be relatively low, due to limited natural fire regimes in seasonally dry tropical forests, increasing the likelihood that these fires are anthropogenic in origin.

5:5:1:4 Terminal Classic ca 0.9-1.2 kyr cal. BP (950-1100 cal. CE)

The Terminal Classic period is associated with the decline, or collapse, of the Classic Maya civilisation. Hypotheses regarding the driver of this collapse range from warfare (Webster, 2000; Palka, 2001; Demarest, Rice and Rice, 2004) to environmental degradation (Paine and Freter, 1996; Rosenmeier *et al.*, 2002; Shaw, 2003) with the background influence of climate aridity an important component (Hodell, Curtis and Brenner, 1995; Hoggarth *et al.*, 2016; Kennett and Hodell, 2017; Evans *et al.*, 2018; Park, Byrne and Böhnel, 2018). The spatial and temporal heterogeneity of the collapse is widely discussed Chapter 2, which highlights the general gradient between the southern and northern lowlands, with the northern centres experiencing this period of *critical transition* later than their southern counterparts. Generally, palaeoenvironmental reconstructions indicate declining human presence on the landscapes associated with the collapse period, with locations recording decreasing soil erosion (Rosenmeier *et al.*, 2002; Anselmetti *et al.*, 2007), and palaeoecological records indicating forest recovery (Mueller *et al.*, 2010). Records that indicate low forest abundances and high disturbance indicators argue that the vegetation is responding to the high-intensity drought event (Carrillo-Bastos *et al.*, 2010; Aragón-Moreno, Islebe and Torrescano-valle, 2012), despite evidence for *Zea mays* (Carrillo-Bastos, *et al.*, 2010). The archaeological record indicates that sites in the south-central Quintana Roo region experience some form of a decline during the Terminal Classic Period (Villamil and Sherman, 2017), whilst the nearest archaeological site to Laguna Esmeralda, Yo'okop, shows site abandonment in the major centres with small populations moving towards a local hydrological source, identified by archaeologists as an aguada (sinkhole that does not fully penetrate the water table) (Shaw, 2000).

The Laguna Esmeralda record shows declining forest abundances, interpreted as forest clearance, and presence of *Zea mays* as evidence for human land-use (*ca* 1000 CE). The period of land-use associated with the Terminal Classic Period is a higher signal of forest clearance compared to the other periods identified in the record (Archaic/Preclassic cultivation period). Cultivation is also evident at Lake Chichancanab (Leyden, 2002), indicating that the landscapes around both lake systems were actively managed during the Terminal Classic. These findings show that the sites were not abandoned and were continuously managed despite the social instability recorded throughout the lowlands. Within the Yucatan Peninsula, Lake Silvituc shows no evidence for *Zea mays* in the record during the Terminal Classic (Torrescano-Valle and Islebe, 2015). From Lake Coba, in the eastern Yucatan, evidence shows a peak in *Zea mays* and a slight (~5%) decrease in forest

abundances between 720-1240 CE, but chronological resolutions cannot confirm whether these indicators reflect land-use during the Late Classic or continuation of activities during the Terminal Classic (Leyden, 2002). Based on archaeological evidence these peaks in the record are likely Late Classic activities, with Coba abandoned during the Terminal Classic. At Lake Tzib, central Quintana Roo, a peak in *Zea mays* and peaks in disturbance indicators (Poaceae, *Cecropia*, Asteraceae) are interpreted to reflect impact on the vegetation through ancient Maya land-use during the Terminal Classic (Carrillo-Bastos *et al.*, 2010). These activities at Lake Tzib and Laguna Esmeralda, respectively, potentially indicate how lake systems were managed during intensive drying periods. As major centres, such as Coba, were abandoned, continued cultivation continued around these less populated regions. These continued periods of land-use are also evident in settlements such as Lamanai, where palaeoecological evidence supports the archaeological evidence for continued occupation throughout the Terminal Classic, by highlighting continued *Zea mays* cultivation (Rushton, Metcalfe and Whitney, 2012; 2020).

The synchronicity between these periods of cultivation are hypothesised to indicate the increasing use of water resources during this period of drought. The differences between the relatively sharp decline in Moraceae/Urticaceae, compared to the relatively stable percentages of the taxa from the adjacent Lake Chichancanab, are assumed here to be driven by different basin sizes, with Laguna Esmeralda reflecting a more local signal compared to the assumed regional catchment of Lake Chichancanab. The complexity of climate change impacting Maya land-use around the Laguna Esmeralda watershed will be discussed later.

5:5:1:5 The Postclassic ca 700-300 cal. BP (1200-1600 cal. CE)

At Laguna Esmeralda, land-use activities during the Postclassic period show a disappearance of *Zea mays* in the record, along with increasing forest abundances. These lines of evidence reflect similar ecological responses to site abandonment during the Terminal Classic period, with forest abundances recovering over the space of ~250 years. Compared to regional records from the Yucatan Peninsula, *Zea mays* appears once again in the Coba record, indicating that the site was reoccupied following the period of abandonment (Leyden, 2002), although arboreal pollen concentrations continue to increase, potentially indicating low levels of activity (Leyden, 2002). Climate conditions show increasing precipitation, with Lake Tzib also continuously cultivated during the Postclassic period (Carrillo-Bastos *et al.*, 2010). At Lake Silvituc, cultivation does not

reappear until the later parts of the Postclassic (~1500 CE) (Torrescano-Valle and Islebe, 2015), highlighting the extent of which the sites around the lake were abandoned during the Terminal Classic. Chichancanab, similar to Esmeralda, shows no evidence for ancient Maya land-use during the Postclassic, with *Zea mays* disappearing from the record along with increasing in arboreal pollen concentrations (Leyden, 2002). In the southern lowlands, despite the temporal discrepancies between when the Terminal Classic occurred in this region, forest recovery is recorded in the Peten Lake districts (Wahl *et al.*, 2007, 2013, 2016), whilst Lamanai shows continued cultivation throughout the Postclassic Rushton, Metcalfe and Whitney, 2012).

The patterns of land-use decline at Laguna Esmeralda, Lake Chichancanab and Lake Silvituc in the Yucatan Peninsula, potentially indicate the movement of the ancient Maya populations towards the coastal peninsula (Aimers and Iannone, 2014; Aimers, 2017). As political capitals such as Chichen Itza became well established during the Postclassic, and the palaeoecological record from Coba indicates continued land-use, the populations managing the landscape around Laguna Esmeralda may have shifted focus towards the coastal regions, explaining the disappearance of *Zea mays* from the record allowing for forest recovery due to a decline in ancient Maya land-use.

5:6 Conclusion:

This chapter presents the first palaeoecological record from Laguna Esmeralda giving new insights regarding how the smaller density populations of the mainland Yucatan Peninsula managed the seasonally dry tropical forest over the past 5000 years. The evidence presented indicates a complicated relationship regarding ancient Maya land-use, with varying degrees of impact on the dry forest ecosystem associated with maize cultivation. The evidence for maize during the Archaic period (*ca* 5.5 kyr cal. BP) is the oldest palaeoecological evidence for maize cultivation in the Northern Lowlands, establishing a new chronological baseline. Periods of cultivation throughout the Preclassic, mirror activities in other locations throughout the peninsula. However, a key difference between the Esmeralda record and other palaeoecological records from the peninsula refers to the extent in which forest cover was influenced by these activities. As centres such as Coba record large reductions in forest cover during the Preclassic, the Laguna Esmeralda shows little impact associated with maize cultivation. Based on the evidence currently available, these findings represent a new understanding regarding the degree of impact on forest cover the ancient Maya had on their environment during the Preclassic. Whilst the larger population densities were seemingly clearing large proportions of the forest to practice agriculture, the less-dense populations at Laguna Esmeralda showed minimal impact on forest cover. These findings present a new scope for understanding the complexity of ancient Maya land-use, by highlighting the variability within the Yucatan Peninsula.

Throughout the palaeoecological record, Laguna Esmeralda highlights various phases of land-use that correlate with palaeoclimate records for drought events. These correlations are particularly evident during the Archaic (~5.5 kyr cal. BP) and the Terminal Classic (~1.0 kyr BP), with impacts on forest cover highlighting the different strategies evident. Between these two periods of impact, forest cover during the Archaic records minimal impact, whilst the Terminal Classic shows an accelerated decline in forest abundances. The evidence for low impact on the seasonally dry tropical forest during the Archaic, and in the later Preclassic, has led to the hypothesis that the intensity of land-use was minimal, on at least a local level (based on relative source theory regarding small basins). Following the abandonment of centres around Quintana Roo during the Terminal Classic period, the evidence indicates increasing land-use activities in the area of both Laguna Esmeralda and

Lake Chichancanab. The underlying influence of the intensive drought event during this period increased the importance of these watersheds for land-use activities.

Laguna Esmeralda offers an important insight regarding the narrative investigating the environmental impact associated with ancient Maya land-use. Throughout the Maya Lowlands, the Preclassic period is identified as a period of cultivation and deforestation across many major centres. These findings lay the basis for arguing that long-term degradation of the environment existed under pressure associated with Maya land-use. The Laguna Esmeralda record indicates that cultivation exists during the Preclassic Period, but forest impact remains minimal and therefore not heavily degraded from land-use. During the Terminal Classic period, when centres were being abandoned and populations were moving throughout the northern lowlands, the highest period of forest reduction is recorded in the Esmeralda record. This research hypothesis that land-use around the Laguna Esmeralda catchment does not show evidence for long term environmental degradation. During various phases of cultivation recorded, forest cover remained relatively stable, with the period during the Terminal Classic acting as an anomalous event for declining forest cover. The influence of the intensive drought event during the Terminal Classic perhaps triggered a societal response to increase the intensity of land-use around Laguna Esmeralda to improve cultivation outputs.

5.7. Author contributions and acknowledgements

This chapter was written by Adam Bermingham who undertook all the pollen preparation and analytics. The upper 195cm of the Esmeralda core were prepared and analysed for charcoal with the remainder of the core analysed by colleagues from Nottingham University. The same colleagues were responsible for the collection of the core between 2014-2016 along with the selection of material and analysis for radiocarbon dating.

Chapter 6 The spatial heterogeneity of pollen deposition across two lake basins and implications for the interpretation of pollen records in the Maya lowlands

6:1 Overview

Palaeoecological records have been used to identify periods of land-use associated with the ancient Maya. To improve the ability to interpret changes in forest abundances, thus reflecting forest cover, an analysis of modern lake surface samples has been completed. Samples were analysed from Laguna Esmeralda and Lake Chichancanab, located close to one another. The implications of the modern pollen assemblages on palaeoecological interpretations are discussed through an analysis of palaeoecological records from both lakes. Based on the interpretations of the link between modern forest cover and modern pollen samples, both Laguna Esmeralda and Lake Chichancanab (Leyden, 2002) were discussed regarding Maya land-use.

6:2 Introduction

Records of ancient Maya land-use are often provided by lake sediments that show abundances of pollen deposited from various taxa, with interpretations measuring the relationships between arboreal and non-arboreal taxa (Leyden *et al.*, 1998; Leyden, 2002; Rosenmeier *et al.*, 2002; Dull, 2007; Fleury *et al.*, 2015). Modern lake surface samples have been analysed throughout the tropics in an attempt to improve the interpretations of the fossil pollen record, whilst investigating how environmental variables such as temperature and precipitation impact the modern assemblage (Bush, 1991, 2000; Rodgers and Horn, 1996; DeBusk, 1997; Correa-Metrio *et al.*, 2011). This improves our ability to reconstruct past environments. Physical characteristics associated with catchment (basin size, local wind direction, local vegetation) also has an important influence on how these past environments are reconstructed through palaeoecological analysis, with quantitative techniques developed to understand the complex nature of pollen deposition into lake catchments (Prentice, 1985; Rodgers and Horn, 1996; DeBusk, 1997; Bunting *et al.*, 2004; Bartlein *et al.*, 2016). From a land-use perspective, these variables have an

important consideration regarding palaeoecological interpretations on forest clearance, whereby different catchments can reflect localised or regional changes in vegetation. Surface samples can aid in these interpretations, by gaining a greater understanding of how the modern catchments reflect forest cover. This is particularly important in ancient Maya research as palaeoecological interpretations for forest reductions associated with land-use has shaped narratives regarding the understanding of the scale and magnitude of forest cover clearance (Byrne *et al.*, 1989; Goman *et al.*, 1998; Leyden, 2002; Dull, 2007; Kennett *et al.*, 2013).

Records of fossil pollen have been used to make interpretations on the intensity of ancient Maya land-use (Leyden, 2002; Mueller *et al.*, 2010; Aragón-Moreno *et al.*, 2012), usually associating high degrees of forest clearance with increasing Maya land-use (Leyden, 1998; Rosenmeier, 2002; Dull, 2007) and forest recovery associated with the abandonment of settlements (Mueller, 2010). The palaeoecological records from Lake Chichancanab (Leyden, 2002) and Laguna Esmeralda (Chapter 5) show contrasting evidence regarding the magnitude of forest clearance associated with land-use activities, despite being adjacent catchments. By analysing surface samples from these lakes, a greater understanding of how these systems reflect the modern landscape will be completed and thus can better inform the palaeoecological records. Variations in basin sizes potentially explain these differences in the palaeoecological record, as Lake Chichancanab is a larger basin size then Esmeralda and therefore potentially capturing a more regional scale signal of forest cover compared to the more localised signal of Esmeralda. Therefore, this research aims to use modern lake surface samples from the two adjacent lake systems (of varying sizes) to understand how the lakes reflect the modern landscape. Based on the findings, a revisitation of the relevant palaeoecological records will be completed to better understand ancient Maya land-use from the smaller density settlements of the Yucatan Peninsula.

6:3 Methods and site summary

To improve the interpretations of the palaeoecological record, an analysis of surface samples from two lakes in the Yucatan Peninsula region of Quintana Roo was completed. Surface samples were collected along a transect of Laguna Esmeralda and Lake Chichancanab by colleagues from Nottingham University (Figure 6.1). The standard protocol of treatment for pollen analysis was completed (Faegri and Iversen, 1989), with 150 pollen grains analysed per sample. Confidence intervals for these counts were performed in the Psimpoll software (Bennett, 2005) (Appendix A). The justification for

this count sum, along with the evidence from the confidence intervals, was due to the focus of this analysis in understanding how the lakes reflected the relationship between tree and non-tree modern vegetation.

To compare arboreal pollen abundances to tree abundance, estimations of modern forest cover were obtained from the Hansen Global Forest Cover dataset (Hansen *et al.*, 2013). Using Geographical information systems (GIS), water bodies were masked to avoid misidentification of water as 'non-trees'. To extract the percentages of tree cover, relative to each sample point, numerous buffers (100-10,000m) were drawn around the individual surface samples. A pre-analysis of the tree cover percentage data, extracted from the buffer analysis, saw strong correlations (>± 0.8) between radii 1000-10,000m. To avoid complications associated with these correlations, only buffers at 100m, 500m, 1000m, 3000m, 7000m were further analysed as they were deemed sufficient to cover the approximation of tree cover from a local (100m) to a more regional (7000m) scale (Prentice, 1985). Hansen's categorisation of trees included in the forest cover data as "canopy closure for all vegetation taller than 5m in height" (Hansen *et al.*, 2013). This classification drove the grouping of assemblages from the pollen analysis. Pollen identified were classified as either "trees", "non-trees" and "other". Due to low taxonomic resolution, pollen identified as Fabaceae and Acanthaceae (which can be represented by both trees and non-trees) were grouped as 'other'. Taxa such as *Quercus*, *Pinus*, *Rhizophora*, Betulaceae and *Avicennia* were also grouped as 'other' because they were deemed not representative of a seasonally dry tropical forest ecosystem due to potential long-distance transportation of the pollen grains. Table 2.1 is highlighted once again here, to show the ecological associations of the taxa associated with trees, non-trees, and others.

To understand the relationship between the modern pollen assemblages and the approximation of tree cover at multiple intervals, multivariate techniques were used (principal component and redundancy analysis) (Legendre and Gallagher, 2001; Paliy and Shankar, 2016). Along with the final buffers analysed for tree cover, other environmental variables were used to constrain the pollen data in the redundancy analysis. The parameters tested were the distance of the surface sample to a cleared shoreline (m) and distance to an assigned forest cover (m).

Finally, to better inform the palaeoecological records from the respective lake systems, data from Laguna Esmeralda (Chapter 5) and Lake Chichancanab (Leyden, 2002) are discussed. To allow for comparisons between both cores, a new "clam" age model

(Blaauw, 2010b) was constructed for the Chichancanab core. Material for radiocarbon dating was based off the original publication of the palaeoclimate record of from Lake Chichancanab (Hodell, Curtis and Brenner, 1995; Leyden, 2002). To avoid issues of taxonomic resolution associated with the identification of pollen from two different palynologists, the results of the Chichancanab palaeoecological record were described to a matching taxonomic resolution that was in the Esmeralda record.

Table 6.1 Reworked table previously shown in Chapter 2 (Table 2.1). Main taxa classified as Trees are highlighted green, non-trees highlighted yellow and those characterised as others are highlighted blue.

Main Species of the seasonally dry tropical forests of the Yucatan Peninsula	**Main Species of the Savannahs of the Yucatan Peninsula**	**Main species of the rainforest ecosystems of the Peten forest, Guatemala**
Bursera Simaruba	Pinus	Fabaceae
Spondias mobin	Poaceae	Moraceae
Brosimum alicastrum	Cyperaceae	Asteraceae
Ficus sp.	Asteraceae	Piscidia piscipula
Moraceae/Urticaceae	Ambrosia hispida (Asteraceae)	Spondias mobin
Combretaceae/Melastomataceae	Moraceae/Urticaceae	Brosimum alicastrum
	Fabaceae	Moraceae/Urticaceae
	Combretaceae/Melastomataceae	Celtis
		Combretaceae/Melastomataceae

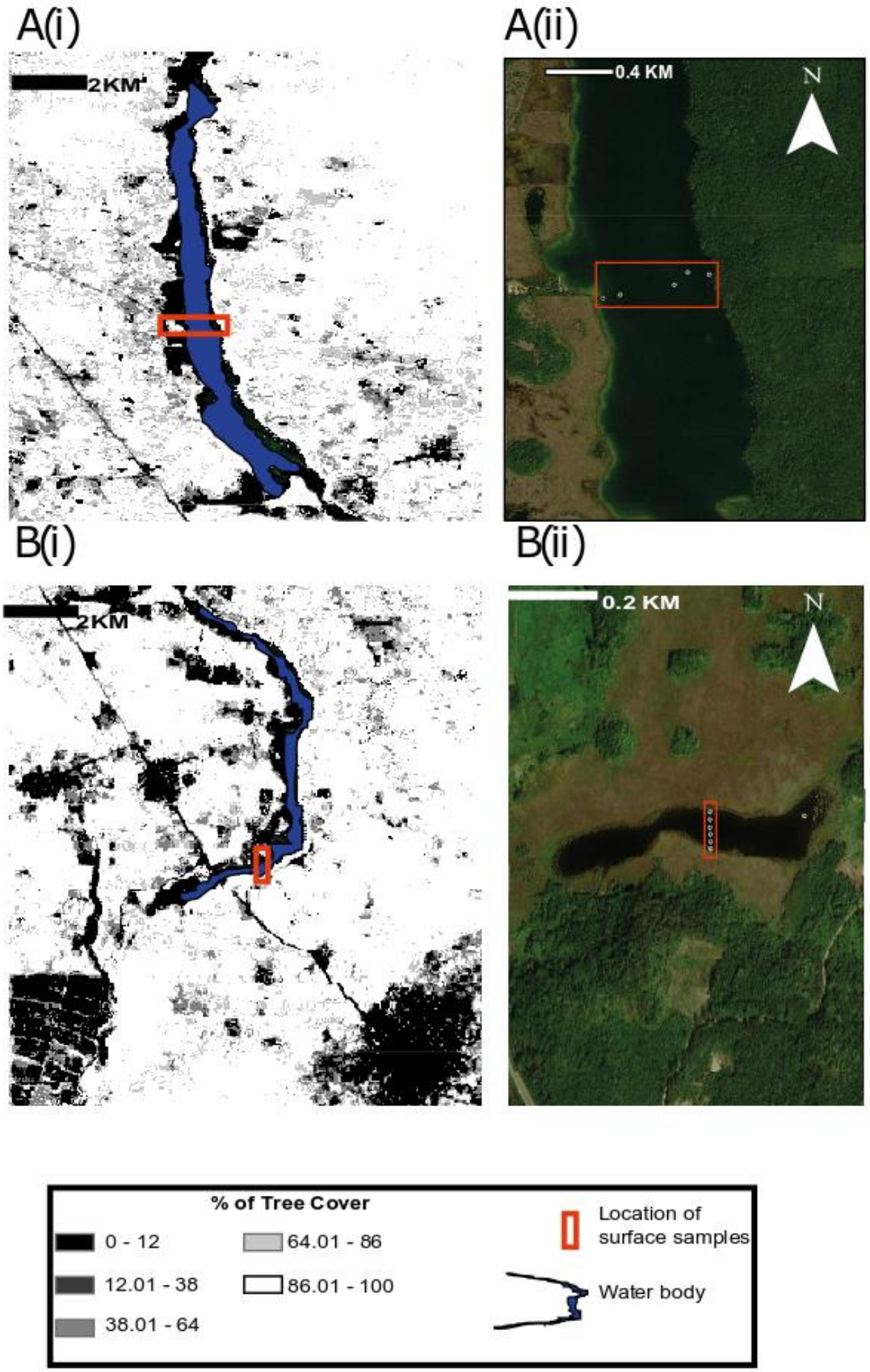

Figure 6.1 Map of the surface sediment transects taken across Lake Chichancanab (A) and Laguna Esmeralda (B). The location of the transects are mapped against the forest cover obtained from the Hansen dataset (Hansen *et al*., 2013). *(Ai) and (Bi) shows the Hansen dataset percentages of tree cover. (Aii) Aerial view of Lake Chichancanab, with*

designated cleared shoreline shown on the west-bank and forest cover on the east bank. (Bii) Arial view of Laguna Esmeralda with designated cleared shoreline on the northern bank and forest cover on the southern bank.

6:4 Results:

6:4:1 Surface sediments

The results of the surface sediment analysis will be split by a brief description of the environmental variables measured (Table 6.1), followed by a comparison between the pollen assemblages from Lake Chichancanab and Laguna Esmeralda. Results will be described along a transect when possible and the names of the samples will refer to their position along the transect (Figure 6.1). For Esmeralda, the first sample (ESM1) is the closest to the southern shore, with samples then moving across a northern transect till ESM 5 being the end sample along the transect. ESM 6 refers to the sample taken outside the transect. For Lake Chichancanab, the first sample (CHICH1) is the closest sample to the western shore, with samples then taken along an eastern transect, finishing at CHICH 6.

6:4:2 Environmental data

The results of the correlation analysis between variables show the distance to forest cover being negatively correlated with all other variables tested, bar tree cover at 7000m where it recorded the strongest positive correlation across all variables tested (0.7). The strongest negative correlation between variables was between tree cover at 3000m and tree cover at 7000m (-0.9), as forest cover at 7000m decreases across all surface samples at Esmeralda compared to increasing at Lake Chichancanab.

For the distance to forest cover and distance to shore measurements, the samples closest to forest cover for Laguna Esmerelda were located on the southern bank (ESM1) and eastern bank for Lake Chichancanab (CHICH6) (Table 6.1). Percentage of forest cover across the selected buffers show the greatest range in values at the 100m and 500m at both Laguna Esmeralda and Lake Chichancanab. For samples adjacent to cleared landscapes, the buffer at 100m captures 0% forest cover from Lake Chichancanab (CHICH1), whilst Laguna Esmeralda records 50% of forest cover (ESM6). CHICH4 also has 0% forest cover at 100m, as it is in the middle of the lake. Ranges in the estimation of forest cover then decrease at higher buffer radii (3000m, 7000m), with Laguna Esmeralda and Chichancanab showing slight variations on a basin-wide scale (Table 6.1)

6:4:3 Pollen assemblages of surface samples

Pollen assemblage data from Laguna Esmeralda and Lake Chichancanab are shown below (Figure 6.2, Figure 6.3). For Laguna Esmeralda and Lake Chichancanab statistical measures of the percentage of tree taxa (mean, quartile range, min-max) are presented in a box and whisker plot (Figure 6.4). The tree percentage data indicates that Laguna Esmeralda (51-74%) has a wider range of percentages compared to Lake Chichancanab (62-74%). The non-tree percentages also show a greater range of abundance from the Laguna Esmeralda surface samples compared to Lake Chichancanab (Figure 6.5).

Moraceae/Urticaceae contribute the highest to the "tree" assemblages with abundances from the Esmeralda samples ranging from 25-61%, compared to the smaller range of Chichancanab (24-39 %). Poaceae contributes the highest to the "non-tree" assemblage ranging from 2-24% across Laguna Esmeralda samples and 2-10% at Lake Chichancanab. *Undiff*erentiated Fabaceae grains were the highest contributors to the "other" assemblage, ranging from 1-5% in the Esmeralda samples and 2-9% in the Chichancanab samples. For samples closest to forest cover in both lakes (ESM1, CHICH6), the highest percentages of Moraceae/Urticaceae are recorded for the Lake Chichancanab (39%), but not in Esmeralda, where the highest abundance is recorded in the next sample across the transect (ESM2 = 62%). Similarly, for samples located closest to the cleared shoreline (ESM6, CHICH1), the highest percentages of Poaceae are recorded in the Chichancanab, but not Esmeralda (ESM3 = 33%) (Figure 6.2).

Table 6.2 Results of the environmental data for the surface samples taken from Lake Chichancanab and Laguna Esmeralda. ESM= Esmeralda; CHICH = Chichancanab. Environmental variables examined were distance to shore

Sample	**Shore (m)**	**Forest cover (m)**	**100m (%)**	**500m (%)**	**1000m (%)**	**3000m (%)**	**7000m (%)**
ESM1	96	50	26.697	52.4	62.36	80.39	77.38
ESM2	84	70	52.4	15.65	62.36	80.39	77.38
ESM3	72	82	51.13	15.65	61.75	80.38	77.39
ESM4	59	105	51.13	9.11	61.75	80.38	77.4
ESM5	40	113	49.65	9.11	61.33	80.32	77.4
ESM6	26	128	49.65	1.18	61.33	80.32	77.41
ESM8	75	103	24.02	54.06	64.84	81.1	79.36
CHICH1	73	420	0	18.05	50.83	77.22	81.95
CHICH2	132	360	2.53	23.38	23.38	77.25	81.99
CHICH4	334	160	0	43.5	57.18	77.35	82.18
CHICH5	410	123	10.7	52.34	59.07	77.52	82.21
CHICH6	474	35	56.02	44.69	60.73	77.72	82.3

(Shore, m), distance to forest cover (Forest cover, m) and tree cover data measured at differing radii (100m, 500m, 1000m, 3000m, 7000m)

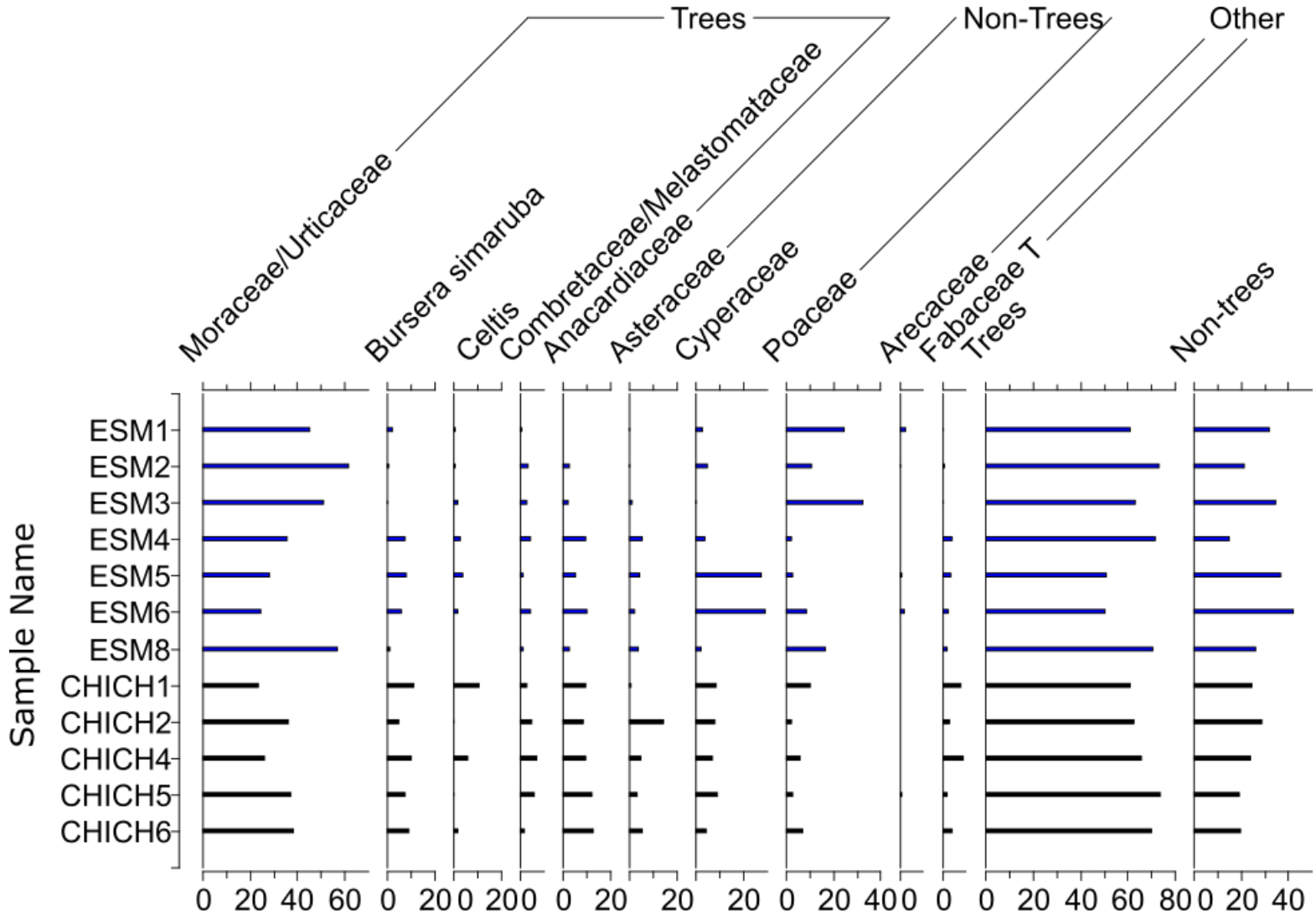

Figure 6.2 Pollen percentages of most important surface sample assemblages from Laguna Esmeralda and Lake Chichancanab. Groupings are done per the classification between ''trees'', ''not trees'' and ''No group''. The groupings do not hold any ecological significance. Different lakes are colour coded Laguna Esmeralda (Blue) and Lake Chichancanab (black).

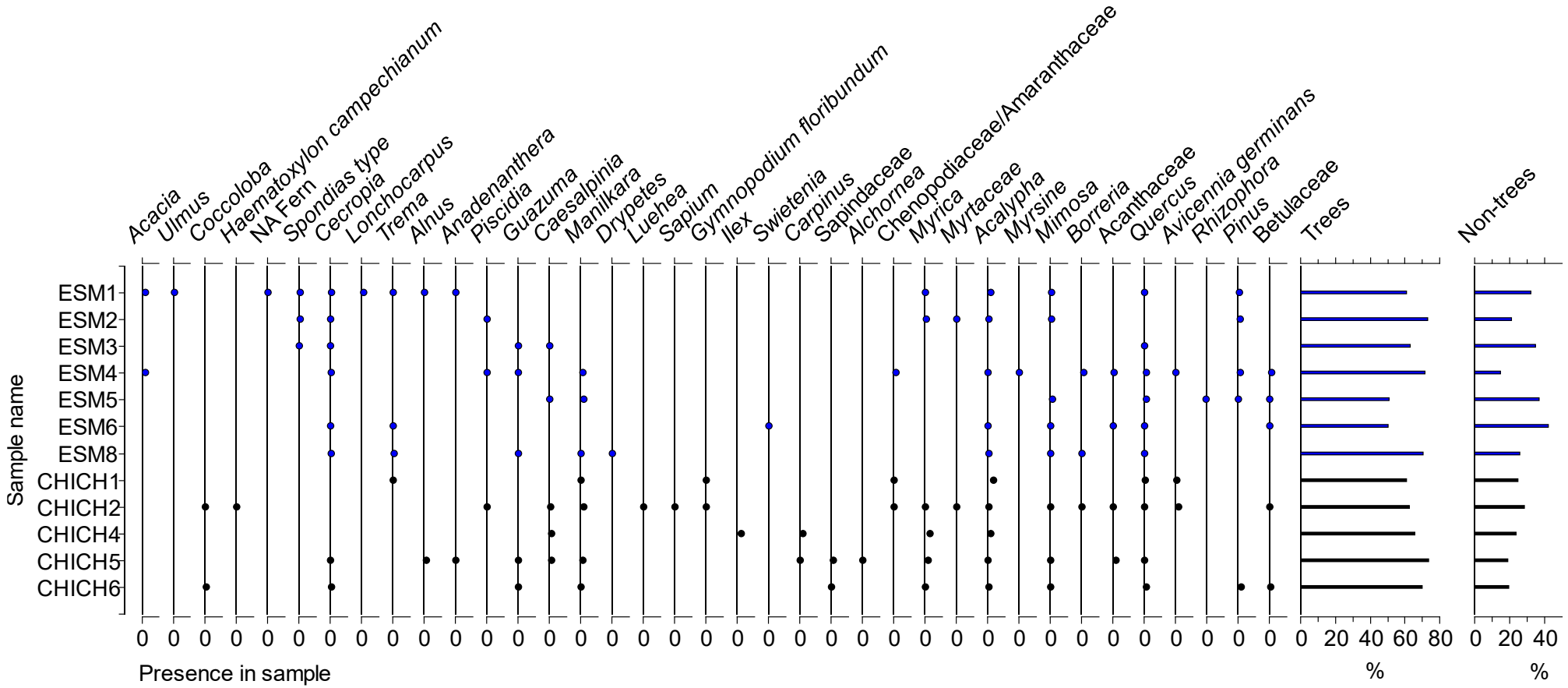

Figure 6.3 Pollen diagram indicating the presence of least abundant taxa from the Laguna Esmeralda and Lake Chichancanab transects. Trees and non-trees graphs represent total percentages from all taxa counted. Different lakes are colour coded with Laguna Esmeralda (Blue) and Lake Chichancanab (black

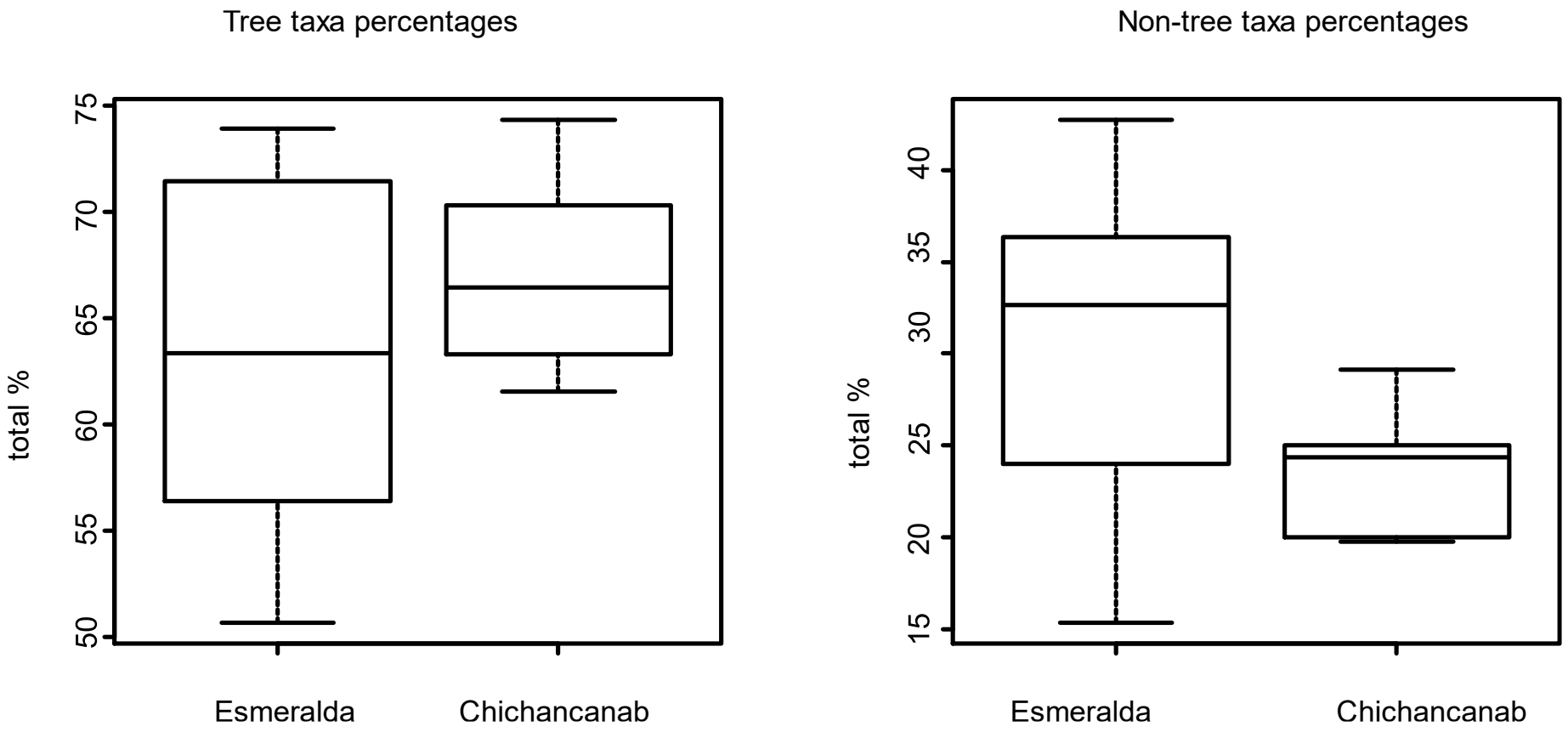

Figure 6.4 Box plot of the tree and non-tree abundances data from Laguna Esmeralda (N=8) and Lake Chichancanab(N=5). The data shows the min-max of each lake (lower and upper black lines). The limits of the box also signify the first quartile (Q1) and third quartile (Q3). Laguna Esmeralda has 7 data points, whilst Lake Chichancanab has 5.

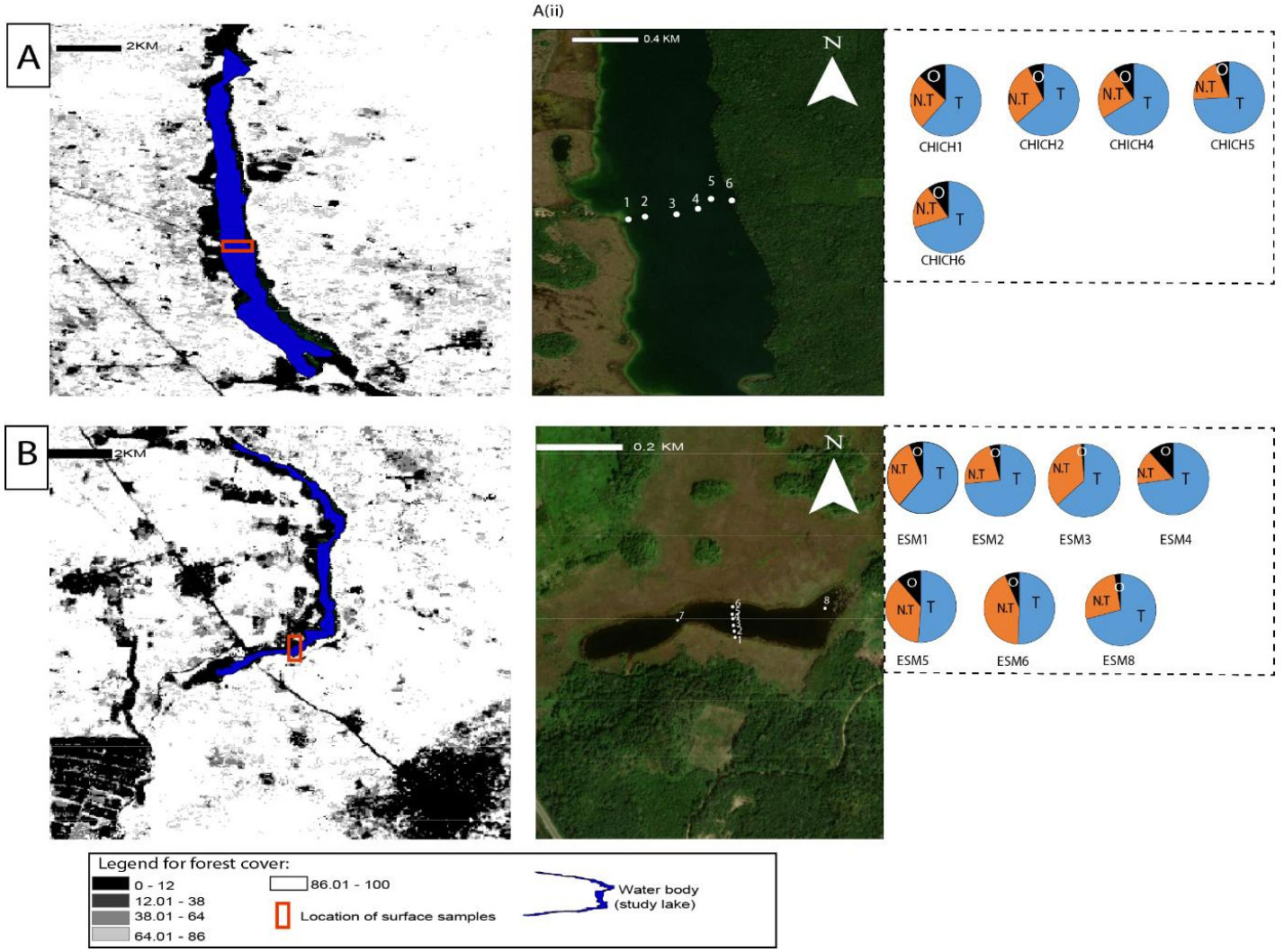

Figure 6.5 Map of the total percentages of trees (blue), non-trees (orange) and other (black) from Lake Chichancanab (A) and Laguna Esmeralda (B). Numbering represents sample name for the respective lakes, samples ESM7 and CHICH 3 were not analysed due to poor pollen concentrations. Pie charts were created based on the sum percentage of tree, non-tree pollen and other abundances. Tree cover dataset is obtained from the Hansen Global Forest Dataset (Hansen *et al.*, 2013)

6:4:4 Numerical analyses

6:4:4:1 PCA analysis of the surface samples.

Due to the small environmental gradient established from the DCA analysis (Appendix A), a principal component analysis (PCA) was completed for the lake surface samples. Differential lake samples are highlighted with different colours (ESM = blue, CHICH = black). The percentage in parentheses on each axis represents the percentage of variance explained by each axis. To avoid label crowding taxa names that had a score higher than +/- 0.4 where highlighted (Figure 6.6)

PCA axis one (PCA1) (Figure 6.6) explains up to 22.5% of the variance recorded in the abundances. Site sample scores indicate that Esmeralda surface samples (ESM4, 5) are positively correlated with PCA1, with all Chichancanab samples (CHICH1-2, 4-6) also positively correlated. Esmeralda samples (1-3, 6-8) were negatively correlated with PCA1. Chichancanab sample (CHICH2), was the strongest positively correlated sample with PCA1 (2.72), with Esmeralda sample (ESM1) the strongest negatively correlated sample (-2.86). Taxa scores show Asteraceae (0.62), Anacardiaceae (0.57) and *Haematoxylon campechianum* (0.45) are the strongest positively correlated with PCA1, with *Bursera* (0.42), Combretaceae/Melastomataceae (0.42) and *Sapium* (0.45) also important (Figure 6.6). *Ulmus* (-0.47), *Spondias* (-0.51) and Poaceae (-0.56) were negatively correlated with PCA1, with Moraceae/Urticaceae (-0.33) and *Lonchocarpus* (-0.47) also along the same axis.

PCA axis 2 (PCA2) explains 15.4% of the variance recorded in the dataset. Site sample scores indicate a positive correlation of Esmeralda (ESM1-4, 8) and Chichancanab (CHICH2) with PCA2 (Figure 6.6). The remainder of the samples from Esmeralda (ESM5-6) and Chichancanab (1, 4, 5-6) were negatively correlated with PCA2. Taxa scores show that Moraceae/Urticaceae (0.43) and *Borreria* (0.51) had the strongest positive correlation with PCA2, with Chenopodiaceae/Melastomataceae (0.33) also strongly correlated. Correlations for taxa indicate that *Carpinus* (-0.52) was the strongest taxon negatively correlated with PCA2, with Bursera (-0.39) also important (Figure 6.4).

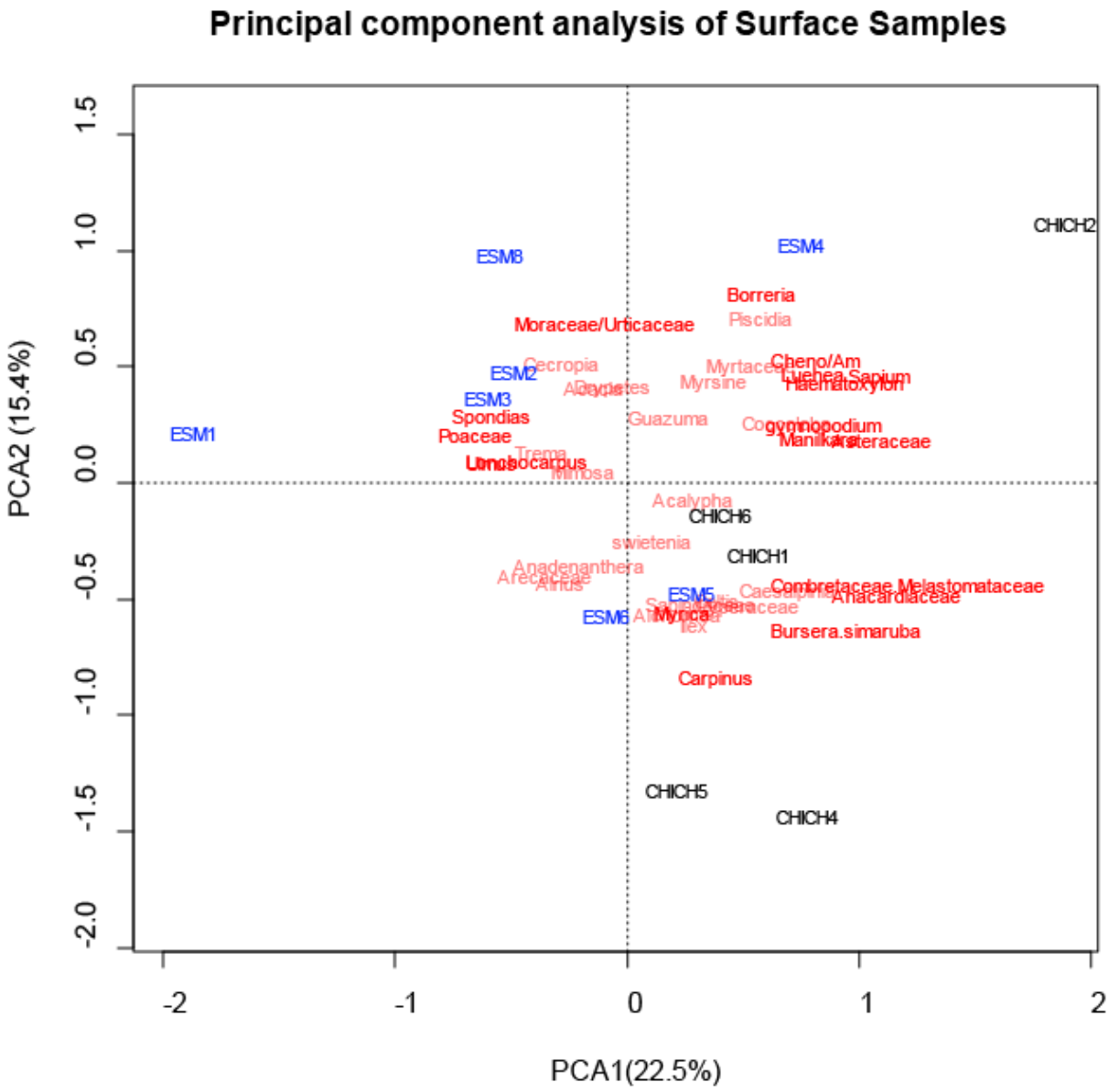

Figure 6.6 Principal component analysis of surface samples from Laguna Esmeralda and Lake Chichancanab. Parentheses values of the PCA axis represent the percentage of variance. Lakes are differentiated through colour coding (Esmeralda = Blue, Chichancanab=Black). Taxon scores mentioned in results are coloured darker to the less significant taxon scores.

6:4:4:2 Redundancy analysis

To understand the underlying influence of the environmental variables (tree cover percentage, distance to shore, distance to forest) on the surface sediment data, a redundancy analysis (RDA) was completed on the dataset. The percentage presented on the parenthesis of each axis explains the percentage of variance explained by that axis (Figure 6.7). Environmental variables are shown in green, individual assemblages in red and the lakes differentiated through colour (ESM = blue, CHICH = black).

A step-wise ANOVA test of permutations indicates, for the constrained redundancy analysis, indicated that tree cover at 1000m (**p-value** = 0.01) and tree cover at 3000m (**p-value** 0.03) are statistically significant. ANOVA tests by "margins", "terms" and "axis" resulted in insignificant results for all permutation runs.

The results of the RDA analysis indicate that distance to shore, distance to forest and tree cover at 7000m are positively correlated with RDA axis 1 (RDA 1). Tree cover at 100m, 500m, 1000m and 3000m are all negatively correlated with RDA 1. Sample scores indicate Esmeralda (ESM4, ESM5, ESM6) and Chichancanab samples (CHICH 1-2, 4-6) are positively correlated with RDA 1, whilst ESM (1-3, 8) are negatively correlated with RDA 1 (Figure 6.7).

Associated with RDA axis 2 (RDA 2), only distance to forest cover and tree cover at 1000m are positively correlated with RDA 2, with all remaining environmental variables (Tree cover 100, 500, 3000, 7000m and distance to shore) negatively correlated. Sample scores indicate Esmeralda samples (ESM 1, 3, 5-6) and Chichancanab samples (CHICH 1, 4) are positively correlated with RDA 2, with remaining samples (ESM 2, 4 and CHICH 2, 5-6) negatively correlated (Figure 6.7).

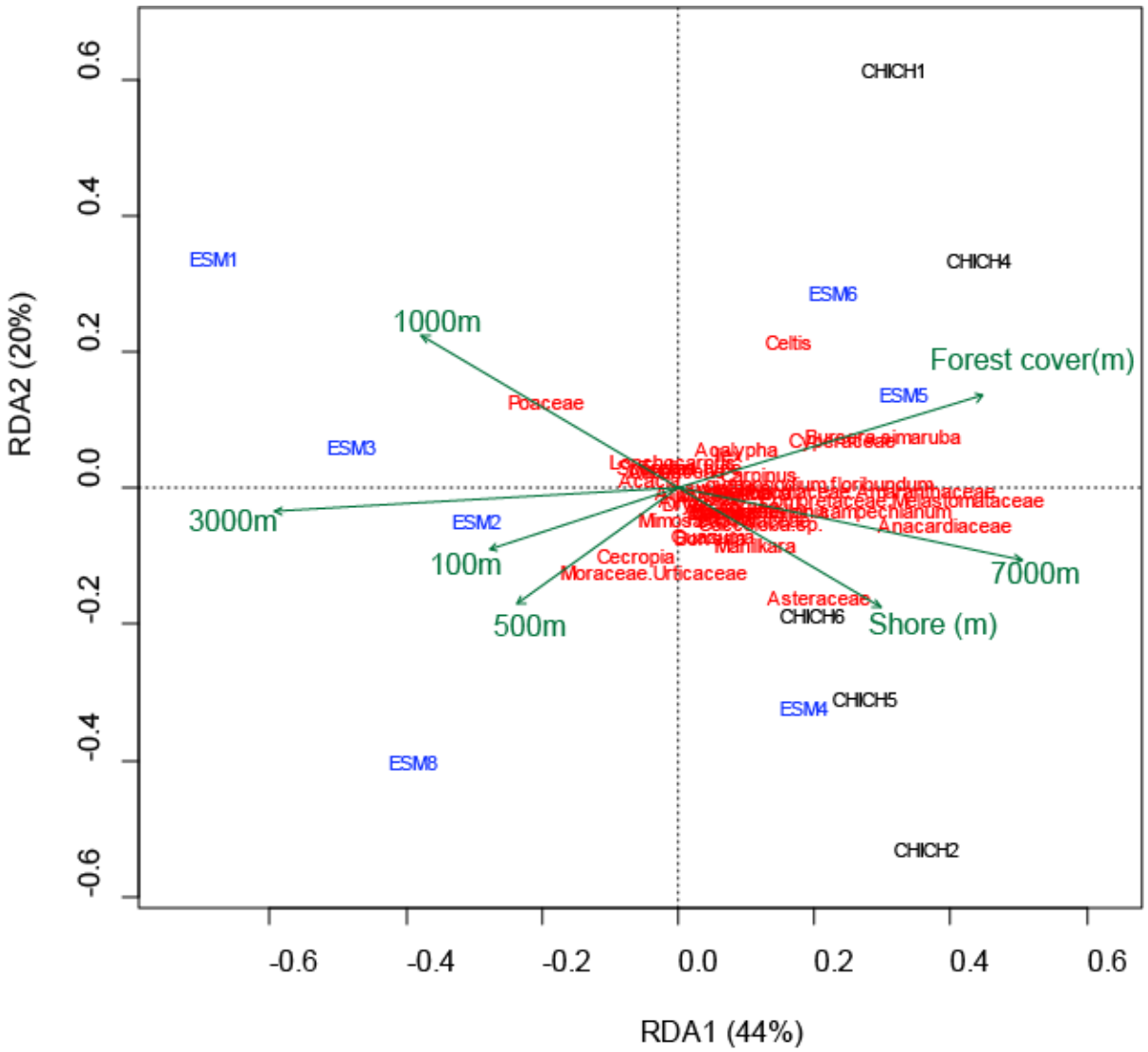

Figure 6.7 Redundancy analysis of the surface samples and the environmental parameters tested. Percentages represent the variance explained by each axis. Lakes are differentiated through colour coding (ESM= Green; CHICH = BLUE). Environmental names were shortened to reduce label clustering with Forest cover (m) representing the distance to cover and Shore (m) the distance of the sample to the nearest cleared shoreline. Numerical values (m) represent the buffer radii for measuring the percentages of forest cover at each sample location.

6:5 Discussion

6:5:1 Relationship between the modern pollen assemblages and forest cover

The modern pollen assemblages from surface samples taken along the transects of Laguna Esmeralda and Lake Chichancanab indicate varying degrees of abundances for tree and non-tree pollen. Evident from the boxplots constructed, Laguna Esmeralda clearly shows a greater range of variability in samples analysed, compared to the shorter ranges of Lake Chichancanab (Figure 6.4). Generally, percentages of tree and non-tree pollen percentages show little variation across the west-east transect of Lake Chichancanab, whilst Laguna Esmeralda shows a higher degree of variability (Figure 6.5). These wider trends of pollen percentages are interpreted here, to argue that Lake Chichancanab represents a homogenous (low-variability) catchment, whilst Laguna Esmeralda represents a heterogeneous (high-variability) catchment. At Lake Chichancanab, despite being located along the Ticul Fault, the water level is only approximately 3m above sea level (Perry *et al*., 2012). The eastern shore of both Laguna Esmeralda and Lake Chichancanab is a scarp of about 20m high, likely marking a fault that is up-trusted to the east (Perry *et al*., 2012). These topographic variations, in comparison to other lakes in the Quintana Roo region, likely impact local wind-flow patterns and thus important characteristics of pollen deposition. Wind directions around Lake Chichancanab and Laguna Esmeralda are easterly. The dominance of the eastern forest cover around Lake Chichancanab, combined with the easterly winds, may explain the dominance of tree pollen recorded in the pollen samples. Also the clear irregular shape of Laguna Esmeralda, and the lack of dominant tree cover on the eastern side of the lake, at a local level, may explain why the pollen shows a higher variability in tree and non-tree percentages compared to Lake Chichancanab.

Another important variable that may be influencing the recording of tree and non-tree pollen at Lake Chichancanab and Laguna Esmeralda relates to lake bathymetry. Based on previous research, Lake Chichancanab shows deeper waters (~14m) on the eastern bank of the lake compared to the western bank (Figure 3.5) (Hodell *et al*., 2005). From data gathered on the fieldwork exhibition to Laguna Esmeralda (Table 3.1), there is no clear indication that water depths follow a similar pattern to Lake Chichancanab. Lakes with shallow water levels, such as those on the western bank of Lake Chichancanab have an increased possibility of sediment resuspension and mixing potentially influencing how the modern landscape is reflected in the surface samples (Evans, 1994). From the evidence of total percentages of tree cover recovered from Lake Chichancanab, combined with

fundamental principles of relative source theory, the larger lake catchment of Lake Chichancanab likely reflects a more homogenous reflection of forest cover, compared to the smaller and heterogeneous catchment of Laguna Esmeralda.

These differences between the homogenous and heterogeneous catchments are potentially explained by differences in basin size. Along the transect where samples were taken, Lake Chichancanab is a larger basin (500m in diameter) compared to Laguna Esmeralda (63m in diameter), which even at its widest diameter (200m) remains smaller than Chichancanab. The influence of basin size on the deposition of pollen into lake catchments has been extensively researched through relative source theory (Prentice, 1985). According to these principles, the larger the basin size the greater the influence of regional pollen sourcing into the lake (Prentice, 1985). Simulations of this theory have shown that the relative source area of a cell (e.g. a lake) measured at 50m would have a pollen source area of 400m, whilst a cell at 400m would have a source area of approximately 1600m (Bunting *et al.*, 2004). The unusual basin shapes of both Esmeralda and Chichancanab means that direct comparisons cannot be made. However, the general theory potentially explains why Esmeralda records more variability in the surface samples, as local vegetation cover primarily drives it, whilst the more homogenous Chichancanab is driven by a regional extent of forest cover resulting in lower variability in samples across the transect.

Along with the physical characteristics of the respective lakes, the differences in variability between the catchments can be discussed through an analysis of the modern pollen surface data, which indicates an underlying relationship between the assemblages and the environmental variables. For Laguna Esmeralda, the heterogeneity of the catchment is shown through the results of the RDA analysis. The pollen abundances from three Laguna Esmeralda samples (ESM1-3) are closely controlled by the only two significant environmental variables tested, Tree cover at 1000m and 3000m (Figure 6.7). No other samples analysed, from Esmeralda or Chichancanab, show a relationship with these significant variables. These buffers represent an interesting metric regarding the transition between “extra-local” (defined as 20-2000m) and “regional” (defined as 2000-200,000m) input of pollen into catchments (Prentice, 1985). The statistics would suggest a strong relationship between the Esmeralda pollen assemblages and the percentages of forest cover at an extra-local and regional buffer, potentially indicating a mixed catchment of local and regional pollen. The catchment of Laguna Esmeralda needs additional analysis to understand this complex system. Whilst none of the Chichancanab samples show a significant relationship with the environmental variables tested, the low variability of the

catchment across the transect indicates that additional surface samples would likely not improve the overall understanding of the relationship between the modern pollen assemblages and forest cover, as additional samples would likely produce similar ratios of tree and non-tree pollen produced here.

The implications of physical basin characteristics on pollen deposition are widely discussed regarding relative source theory principle (Han *et al.*, 2017; Poska *et al.*, 2011; Bunting *et al*., 2010; Prentice, 1985). Parameters such as basin size (Bunting *et al*., 2005; Sugita, 1994; Prentice,1985) and wind direction (Song *et al.*, 2004; Small and Antle, 2003; Luna *et al*., 2001; Giddings *et al.*, 1997) are particularly problematic when attempting to understand the complex processes of pollen deposition. The dominant easterly winds around Lake Chichancanab and Laguna Esmeralda may be impacting the dominating forest signal recorded from the surface sample analysis, with forest cover dominant on the eastern bank of Chichancanab compared to Esmeralda. As the number of samples examined are relatively low, whether the low variability of pollen recorded at Lake Chichancanab is systematic of underlying pollen transportation mechanisms, controlled by wind direction, is difficult to determine. Secondly, under most experimental models of pollen deposition, the simulated lakes are relatively "normal" in shape (i.e. circular with pollen input equal from all directions). The shapes of Laguna Esmeralda and Lake Chichancanab are complex regarding how one might infer relative source area. Whilst being long in diameter, they are narrow in width. This potential means that their source area could be impacted by long-distance transportation of pollen through the lake, particularly during times of high water, when the lakes are hypothesis to have been connected (Hodell *et al*., 2005). These complex processes are likely to have important impacts on interpretations of human impact on the environment, with the spatial representation of forest reduction likely impacted by a combination of actual clearances and pollen dispersal factors.

6:5:2 Comparison of ancient Maya land-use at Laguna Esmeralda and Lake Chichancanab

This study of the catchment properties of two key records in the region enhances the understanding of ancient Maya land-use in the region. One of the major difficulties in the comparison is that sample size per era is different between Lake Chichancanab and Laguna Esmeralda (Figure 6.8 & Figure 6.9). Future work has the potential to increase the resolution of samples around important periods, particularly the Terminal Classic, but at this moment comparisons are limited.

The palaeoecological records from the lakes identify that cultivation existed in Laguna Esmeralda during the Archaic and Preclassic periods (*ca* 3400 BCE, 2000-1300 BCE) with no evidence for cultivation during the Classic period (*ca* 200-700 CE) (Chapter 5). From Lake Chichancanab, the short core covers the past 2000 years (cal. BP) (Leyden, 2002), and therefore no evidence is available to suggest synchronicity between cultivation in both lake systems during the Archaic (prior 2500 BCE) and Early Preclassic (*ca* 2500-1500 BCE). Evidence for maize cultivation first appears at Lake Chichancanab during the Classic period (Leyden, 2002), indicating a potential shift in land-use location. The Terminal Classic period (*ca* 750-1100 CE), represents the only established synchronised evidence for cultivation around Laguna Esmeralda and Lake Chichancanab. Following this, no evidence for cultivation exists in either record, with Laguna Esmeralda showing evidence for maize cultivation during the Modern period (*ca* 1900 CE). Associated with these periods of ancient Maya land-use, both records show contrasting evidence for the degrees of forest clearance around each lake. During the later parts of the Preclassic (*ca* 200 BCE – 200 CE), with no evidence for cultivation evident, both records show high abundances of Moraceae/Urticaceae and *Bursera* (Figure 6.8 and Figure 6.9). During the Terminal Classic (*ca* 750-1100 CE), with cultivation evident around both catchments, the magnitude of the decline of Moraceae/Urticaceae abundances differs between Laguna Esmeralda and Lake Chichancanab. Evidence for forest decline, and thus interpreted ancient Maya impact, at Lake Chichancanab is minimal (~5% reduction in Moraceae/Urticaceae), compared to Laguna Esmeralda (~40 % reduction in Moraceae/Urticaceae). It is during this period where the greatest differences in the palaeoecological record are recorded between Lake Chichancanab and Laguna Esmeralda. During the Postclassic (*ca* 1200 CE), following the period of impact, forest recovery at Lake Chichancanab occurs between 1000-1200 CE, exceeding pre-impact abundances (Figure 6.9). At Laguna Esmeralda, throughout the same period, forest recovery occurs between 1000-1400 CE but does not reach pre-impact levels (Figure 6.8)

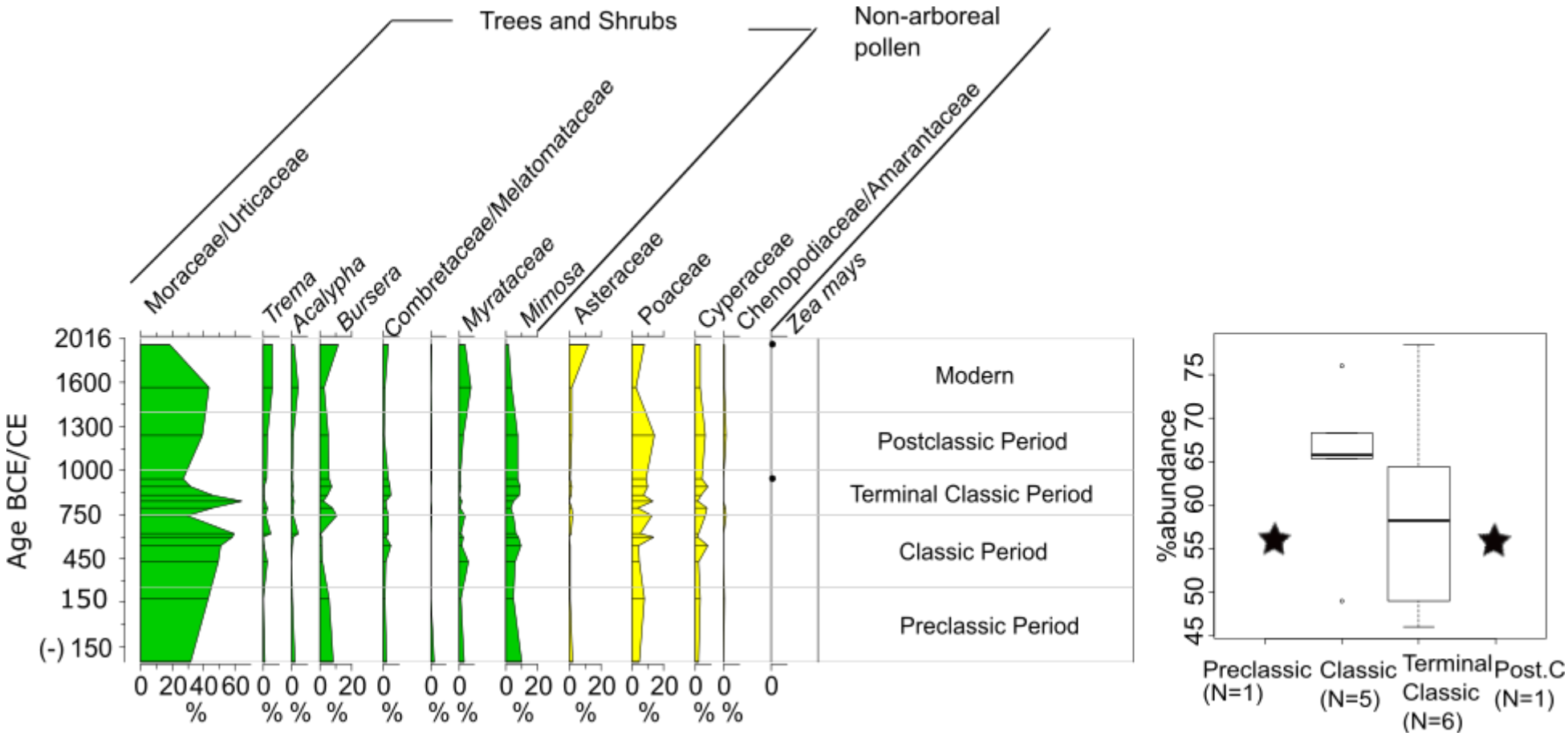

Figure 6.8 Palaeoecological record from Laguna Esmeralda across the discussed ancient Maya periods. Taxon shown were selected to match the Chichancanab record. Boxplots next to the palaeoecological record shows the variation in forest abundances across Maya periods in both records.Post.C = Post Classic period. A limit of 5 samples per period (N=5) was selected as an appropriate sample size to display boxplots. When = <5 a symbol was shown of the mean forest abundances for all samples across that period.

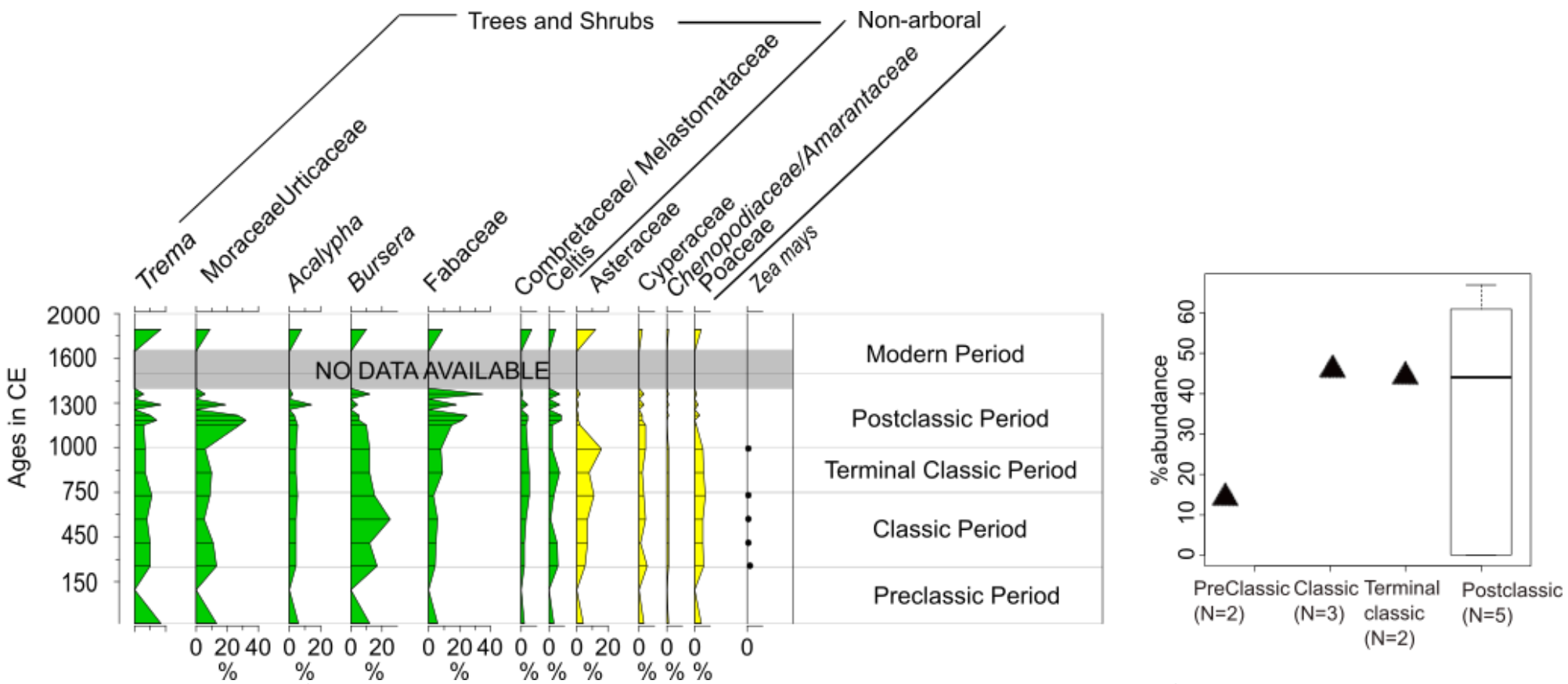

Figure 6.9 Palaeoecological record taken from the Lake Chichancanab core (Leyden, 2002). Box plot constructed over the important ancient Maya periods of tree taxa percentages. From the original publication, taxonomic resolution for some results were given at family level, to allow for matching with the Laguna Esmeralda record. A limit of 5 samples per period (N=5) was selected as an appropriate sample size to display boxplots. When = <5 a symbol was shown of the mean forest abundances for all samples across that period.

6:5:3 Implications for the interpretations of Maya land-use based on modern pollen surface analysis

The analysis of the palaeoecological record from Laguna Esmeralda (Chapter 5) assumed that the small basin size of the lake represented a local indication of ancient Maya land-use. These assumptions have been strengthened by the highly variable abundances of pollen recorded across the lake. Previous interpretations of the Lake Chichancanab record associated variations of forest abundances with increasing and decreasing pressures associated with ancient Maya cultivation (Leyden, 2002). From the analysis of the surface sample data, it is hypothesised that local variations in forest cover cannot be established from Lake Chichancanab and that variations represent a regional scale variability in forest cover. These interpretations have important implications for the understanding of ancient Maya land-use around the adjacent lake systems.

The palaeoecological record from the Terminal Classic period represents a unique opportunity to examine how adjacent lake systems can portray alternate narratives associated with ancient Maya land-use. As both records record maize cultivation during this period (900-1000 CE), it is assumed similar land-use practices were evident around the catchments. However, the palaeoecological interpretations for the magnitude of forest clearance around Lake Chichancanab (low) and Laguna Esmeralda (high) would indicate contrasting methods of cultivation, where one catchment was heavily cleared (Esmeralda), whilst the other remained relatively untouched (Chichancanab). A closer examination of the surface sample dataset better informs the understanding of the sensitivity of the palaeoecological records in capturing forest clearance events. The modern pollen assemblages from Lake Chichancanab and Laguna Esmeralda show a potential relationship between a samples proximity to localised clearances and the abundances of non-tree pollen recorded. Despite these samples (ESM5-6; CHICH1-3) not showing a significant relationship to the distance to the cleared environmental variable, their implications for the interpretations for ancient Maya land-use remain important. The modern pollen from Laguna Esmeralda, show a stronger signal of non-tree pollen in samples closer to the cleared shoreline compared to Lake Chichancanab, where tree pollen relatively consistent throughout the transect, with slight increases in non-tree pollen towards the cleared landscape showing some degree of sensitivity to local vegetation. This is inferred here to suggest that the Esmeralda samples are more sensitive to local changes in vegetation

compared to Chichancanab, which would support the hypothesis between a local vs. regional catchment. From the perspective of ancient Maya land-use during the Terminal Classic, the reductions in arboreal pollen from the Laguna Esmeralda palaeoecological record was likely driven by local scale clearances of the forest, producing a strong signal for forest decline. Compared to Lake Chichancanab, it remains plausible that these localised clearances occurred around the catchment, but the palaeoecological record was not sensitive enough to detect these on a similar scale to Esmeralda, indicating a more regional interpretation of forest cover. It remains unclear whether the sensitivity of the Laguna Esmeralda record is producing an amplified signal of forest reduction, whereby one bank was locally cleared, or if it represents the true extent of clearances around the catchment. This is shown through the modern surface sample examination, whereby the sensitive samples record high non-tree pollen percentages, despite the southern bank being covered with forest. Potentially the palaeoecological record from Esmeralda is a more accurate representation of the forest cover clearance around the catchment, with the Chichancanab record highlighting that the activities were not extensive enough to largely impact the wider extent of regional forest cover.

Whilst this research has established a potential contrast regarding the sensitivity of the records in recording forest clearances, the importance of the local forest around the respective catchment is an important consideration for the understanding the forest clearance associated with ancient Maya land-use in smaller density settlements. From the palaeoecological record around Chichancanab, the relatively high abundances of tree pollen associated with the periods of cultivation have been interpreted to indicate that the forest cover clearance associated with ancient Maya activities was not extensive enough to impact regional forest cover. However, the influence of the dominant eastern forest cover cannot be discounted as a potential driver of this low-variability, low-sensitivity, catchment. As previously discussed regarding wind-direction, the combination of easterly winds and an eastern source of tree pollen may have resulted in a bias towards the eastern forest cover, where both the palaeoecological and modern dataset are reflecting changes in the eastern bank. This bias potentially explains why the intensive localised activities recorded at Esmeralda during the Terminal Classic are not evident at Chichancanab. The relatively stable abundances of arboreal pollen from the palaeoecological record are reflecting changes in the eastern bank of the lake, where tree pollen may be over-represented, with western bank clearances potentially producing a subdued signal. Questions remain regarding how localised impacts on this eastern forest cover would be reflected in the palaeoecological record, despite a regional source of pollen hypothesised

for Chichancanab. Experimental based approaches to understand the sensitivity of rain forest changes in large lakes (>1km in diameter) has shown a sensitivity of the records to detect small changes in the rainforest cover (Whitney *et al.*, 2019). Whilst Chichancanab would not be a large lake under this definition, it could imply that localised clearances of the eastern bank would be recorded from a palaeoecological perspective. These findings represent important considerations for the interpretations of palaeoecological records of ancient Maya land-use. Understanding the sensitivity of lakes to localised changes in the environment, along with the influence of local vegetation, can greatly influence interpretations regarding the scale and intensity of past forest clearance events.

6:6 Conclusion

This research presents an analysis of modern surface samples taken from adjacent lake systems in the Quintana Roo region of the Yucatan Peninsula, Laguna Esmeralda and Lake Chichancanab. Whilst there remains an uncertainty associated with the predictive capabilities of the environmental variables in understanding the modern pollen spectra, it is a first step in understanding the modern pollen deposition characteristics of both systems. Environmental variables, such as wind direction and basin size, are important considerations regarding the deposition of pollen into the respective lakes and future work can explore such influences to determine how these variables influence the sensitivity of the catchments in recording vegetation change. Based on the assumptions of these underlying variables and contrasting abundances of tree pollen recorded from the surface sample, this research concludes that Laguna Esmeralda is capturing a local signal of forest cover compared to the regional catchment of Lake Chichancanab. Both records have the potential to be sensitive to localised clearances or changes in the dominant forest cover, as future investigations can improve the understanding of these complicated catchments.

Regarding the implications for the interpretations of ancient Maya land-use, the sensitivity of these records could indicate an amplified or subdued signal of localised clearance events. From this research, the two catchments provide an interesting perspective regarding the low-densities populations impact on forest cover around the respective watersheds. Land-use from the Terminal Classic was contextualised to reveal that land-use activities were localised around Laguna Esmeralda, and potentially Chichancanab, although the impact was not intensive enough to influence the wider extent of regional forest cover. These findings highlight that adjacent lake systems can have contrasting interpretations regarding the intensity of ancient Maya land-use when examined in isolation. Although, by

adding context regarding the modern catchments of the respective systems and examined in conjunction rather than isolation, a clearer picture regarding the environmental impact on forest cover caused by ancient Maya land-use activities can be obtained.

6.7 Author contributions and acknowledgements

This chapter was written by Adam Bermingham who analysed all the pollen samples and completed statistical analytics on the dataset. Surface samples were collected by colleagues in Nottingham University, U.K. Pollen data from Lake Chichancanab was provided by the original publication of Leyden (2002), where additional information was gathered for construction of the new age model. All GIS techniques were completed by Adam Bermingham with data on forest cover obtained from Hansen *et al*., (2013).

Chapter 7 The land-use strategies of the "shrimp in the mud" Maya

7:1 Introduction

This thesis improves the understanding of the variability of ancient Maya land-use in the Yucatan Peninsula by focusing on two regions that were occupied by low-density populations. Thompson *et al.*, (1962) referred to the over-representation of archaeological research in the Maya Lowlands focusing on the "Rheims and Yorks of the Maya areas" and called for researchers to begin focusing on the "Stowe-in-the-Wold and Shrimp-in-the-mud type of Maya centre". This research focused on these "Shrimp-in-the-mud" settlements from a palaeoecological perspective. The rationale behind this perspective was due to the over-representation of palaeoecological records in current research that were focused on the large urban regions of the Maya region. These previous records influenced the narrative regarding the relationship between the ancient Maya and their environment, with evidence for deforestation (Paine and Freter, 1996; Whitmore *et al.*, 1996; Leyden, 2002; Mueller *et al.*, 2010; Anderson and Wahl, 2016) influencing interpretations for potential environmental causes to the eventual decline of the Classic Maya Civilisation (ca 750-1100 CE) (Shaw, 2003; Diamond, 2005; Cook *et al.*, 2012). These models for long-term environmental exploitation required a greater understanding of the variability of land-use throughout the Maya region, to determine if deforestation was as extensive as the palaeoecological records from higher-density settlements suggest.

Throughout the three empirical chapters (Chapter 4-6), a combination of modern and fossil pollen was used to interpret ancient Maya land-use in seasonally dry tropical forest ecosystems in these smaller density settlements, thus addressing the aim set out (section 1.6). The investigation of Ambergris Caye presented the first palaeoecological reconstruction of ancient Maya land-use on an island site (Chapter 4), showing evidence for the management of the terrestrial dry forest ecosystem. The investigation from Laguna Esmeralda also showed similar levels of impact within the dominant dry forest ecosystem (Chapter 5), highlighting that lower density settlements provide new perspectives regarding forest cover clearances. Along with phases of forest clearance, the comparison between land-use inland (Figure 5.3) and coastal (Figure 4.3) lower-density settlements indicates that access to resources had an important influence on the cultivation strategies in

these regions, with coastal inhabitants less reliant on terrestrial subsistence (Q1, section 1.6). Interpretations on the scale of ancient Maya clearance on forest cover is closely associated with changing percentages of arboreal and non-arboreal pollen (Figure 2.7), which drove the justification for the third empirical chapter on understanding how the modern forest was represented in two adjacent lake systems (Lake Chichancanab and Laguna Esmeralda) (Chapter 6). These sites framed the understanding of how lake properties influence the interpretations of ancient Maya forest clearance, linking into the understanding of land-use from lower-density settlements. The findings from these three empirical chapters show that land-use, associated with periods of cultivation, had low impacts on forest cover (Q4, section 1.6). The palaeoecological records from Ambergris Caye (Chapter 4) and Laguna Esmeralda (Chapter 5) both provided new, regional, chronological baselines for the onset of cultivation in the respective regions, preceding current archaeological and palaeoecological investigations (Q2, section 1.6). These findings for cultivation during the Archaic are used to develop the understanding of potential drivers for the onset of management of the seasonally dry tropical forest ecosystems.

The results of this thesis highlight the value of researching land-use in smaller density settlements and improve how the respective areas of this research were used during periods of instability. The impact of climate change on the demise of the Classic Maya society is well documented (Hodell, Curtis and Brenner, 1995; Shaw, 2000; Medina-Elizalde *et al.*, 2010; Luzzadder-beach, Beach and Dunning, 2011; Turner and Sabloff, 2012; Carrillo-Bastos, Islebe and Torrescano-Valle, 2013; Dunning *et al.*, 2014; Iannone, 2014), but this research takes this understanding one step further by correlating land-use strategies with periods of drought and analysed from a societal perspective (Q3 section 1.6).

7:2 Ancient Maya impact on Forest cover

Ancient Maya impact on forest cover is one of the continued narratives which determine a negative relationship between the society and their environment (Shaw, 2003; Diamond, 2005; Dull, 2007; Lozano-García *et al.*, 2010; Kennett and Beach, 2013). Combined with evidence for intensive drought during the Terminal Classic Period (*ca* 750-1100 CE) (Hodell, Curtis and Brenner, 1995; Hodell, Brenner and Curtis, 2005; Medina-Elizalde *et al.*, 2010; Kennett *et al.*, 2012), palaeoecological evidence for deforestation contributes to the narrative for environmental degradation as being a key contributor to the societal collapse of the ancient Maya. Ecological theories for the decline of the Classic Maya civilisation are explained through conceptual models, which incorporate ecological resilience theories alongside palaeoenvironmental proxies (Shaw, 2003; Diamond, 2005). These models hypothesise an over-exploited environment that succumbs to intensive drought events, resulting in the "collapse" of the Classic Maya (Hodell, Curtis and Brenner, 1995; Shaw, 2003; Diamond, 2005; Anselmetti *et al.*, 2007; Oglesby *et al.*, 2010). Whilst the influence of climate change on the demise of many urban and rural centres throughout the ancient Maya region cannot be underestimated, the probability of these drought events as acting as a sole catalyst fails to incorporate much of the inter-site variability and societal complications.

7:2:1 Intensity of forest clearance recorded between higher and lower density settlements

Palaeoecological investigations into the forest cover impact have provided crucial information regarding the intensity of forest clearance associated with periods of cultivation, often used as a key piece of evidence to indicate the degree of environmental degradation associated with these activities. Across the highland and lowlands, as well as different ecosystem types, the Preclassic represents a period of intensified forest clearance around numerous records (Lake Coba, Lake Salpeten, Petapilla Pond and Agua Caliente) often attributed as a product of societal development (Leyden, 1987; Leyden *et al.*, 1998; McNeil *et al.*, 2010; Walsh *et al.*, 2014). Recorded through percentage abundances between arboreal and non-arboreal pollen, these records are closely associated with Maya urban regions (Coba, Tikal, Copan, Uxbenká), with Lake Salpeten also showing evidence for settlements directly within the watershed. These intensive periods of forest cover

clearance are not reflected in the records from lower-density settlements, representing an important distinction between low and high-density settlements (Figure 7.1). Two potential explanations are discussed here to determine these contrasts on forest cover impact. One reason could be that the smaller density settlements were temporarily used by the ancient Maya, with the high clearance events from the higher density settlements a result of continuous management of the landscape. Another explanation for the differences between the high-intensity clearances and low-intensity clearances as being an artefact of palaeoecological interpretations, with the reductions in arboreal pollen representing localised clearances for the construction of built monuments, meaning masking of the true extent of forest cover. To understand if these ecosystems were occasionally used by the ancient Maya, developments regarding the role of smaller density settlements in the political establishment of the ancient Maya needs to be improved (Iannone, 1996; Garber, 2004; Hoggarth *et al.*, 2014). Currently, the understanding of land ownership from a lower-density settlement perspective is unclear and therefore this research alone cannot distinguish if these environments were politically or locally controlled. Archaeological evidence from the medium density site of Baking Pot in the Belize River Valley shows some degree of elite residency in these less-dense regions (Piehl and Awe, 2010; Hoggarth *et al.*, 2014), and therefore potentially indicates that these smaller density settlements were politically controlled by the wider-kingdom structure. The archaeological evidence from Ambergris Caye and Laguna Esmeralda does not show similar evidence for elite residency and therefore difficult to determine what social controls influenced how the landscapes were used. Based on the palaeoecological data presented in this research, it remains possible that the low levels of impact reflect an occasional use of the dry forest ecosystem, with the temporal resolution too low to capture the short-term impact on forest cover. Regarding the differences between the two types of settlement as being the result of palaeoecological interpretations, Chapter 6 highlights how two adjacent lakes can differ in interpretation, regarding forest cover impact, when environmental variables are not considered as influences on the palaeoecological record. As none of the records in this research show evidence for a similar scale of architecture in the records that show intensive periods of deforestation, it is possible that these constructions are influencing palaeoecological interpretations regarding the impact on forest cover. If it is found that the records from the higher density settlements are a true representation for the degree of the impact associated with the ancient Maya, then the lower-density settlements present a new baseline regarding a low-intensive method of land-use. Regardless of the underlying differences between higher and lower density settlements, this low intensive model for

forest cover impact provides a greater insight into the variability of ancient Maya land-use, informing current models attempting to understand the complex feedback systems between deforestation and drought. These models that use the 'extreme' basis for deforestation (Oglesby *et al.*, 2010) can now incorporate the new records into the understanding, to show the episodes of forest clearance were highly variable across the ancient Maya region.

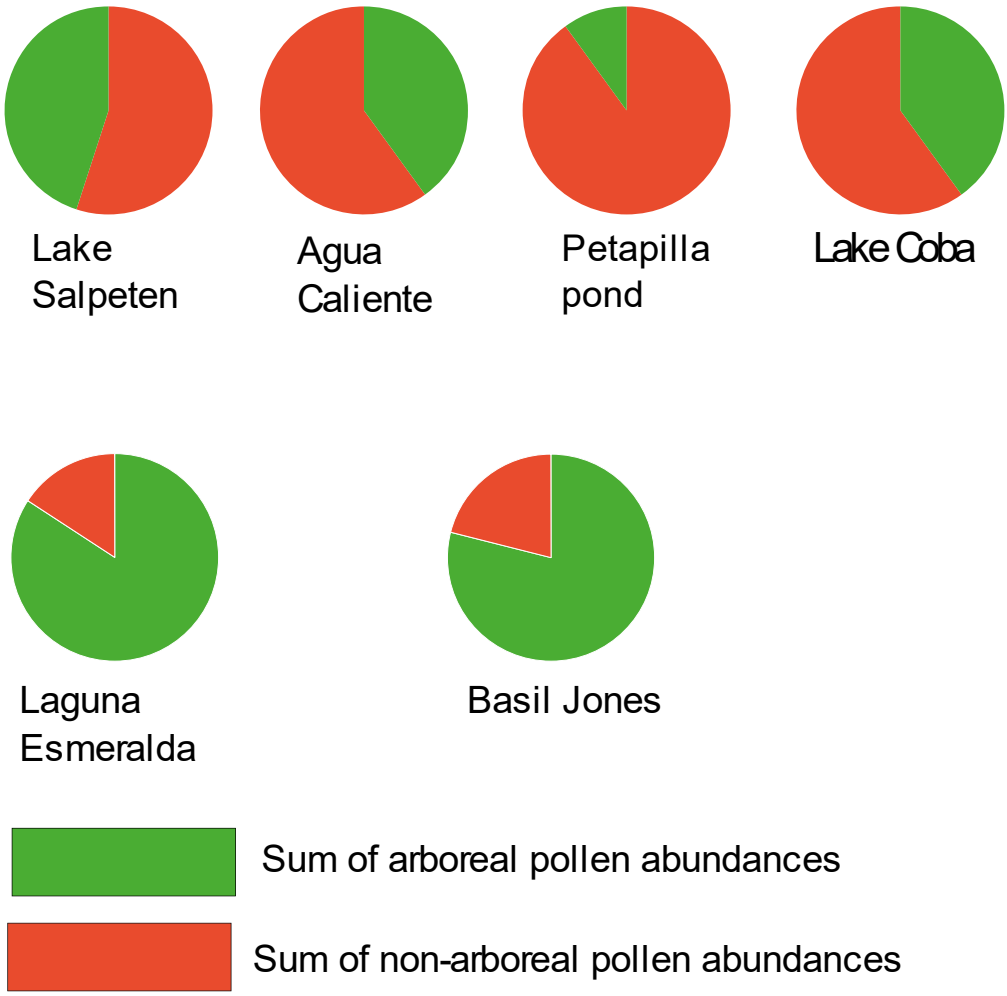

Figure 7.1 A comparison between the Laguna Esmeralda and Basil Jones palaeoecological records to previous records that indicate high degrees of forest clearance during the Preclassic. Data found in original publication: Lake Salpeten (Guatemala)(Leyden, 1987), Agua Caliente (Belize)(Walsh and Prufer, 2014)*, Petapilla pond (Honduras)(McNeil et al., 2010), Lake Coba (Eastern Quintana Roo), Laguna Esmeralda (Central Quintana Roo), Basil Jones (Ambergris Caye).*

7:3 Ancient Maya land-use in the seasonally dry tropical forest ecosystem

Seasonally dry tropical forests represent another important contextual aspect of this thesis regarding the land-use strategies of the ancient Maya from lower-density settlements. Both the ecological characteristics and drought adaptability of seasonally dry forests likely had important implications regarding the use of these ecosystems. Throughout investigations into the land-use strategies of the ancient Maya, wetland ecosystems have seen a particular focus, potentially driven by the finding for early *Zea mays* cultivation in Belize by ~5.0 kyr cal. BP (Jones, 1994; Pohl *et al.*, 1996). The increased focus on wetland ecosystems have developed important ecological models regarding how these systems were used during initial cultivation, but also in response to periods of climate instability (Luzzadder-beach, Beach and Dunning, 2011; Beach *et al.*, 2015; Beach *et al.*, 2019). As our finding for cultivation in the dry forest ecosystem of Laguna Esmeralda (~5.6 kyr cal. BP), sets a new chronological baseline, these ecosystems were as, if not more, important ecosystems for the ancient Maya.

7:3:1 Chronological baselines for cultivation in dry forest ecosystems and their role in ancient Maya settlement

Before this research, the understanding of ancient Maya land-use in the dry forest ecosystems of the Yucatan Peninsula (YP) was limited in the number of sites investigated. The earliest evidence for cultivation was previously established at Lake Silvituc (western Y.P = 4.0 kyr cal. BP) (Torrescano-Valle and Islebe, 2015), then Lake Tzib (southeastern Y.P = 3.5 kyr cal. BP) (Carrillo-Bastos *et al.*, 2010), Lake Coba (northeastern Y.P = 2.8 kyr cal. BP) (Leyden, Brenner and Dahlin, 1998) and then Lake Chichancanab (central Y.P = 1.7 kyr cal. BP) (Leyden, 2002). This would indicate a large, regional, temporal range where cultivation was established, with it taking between 4.0-1.7 kyr cal. BP, to be evident in the west-central-eastern Yucatan Peninsula. However, the records presented in this research provides new baselines for both the central and eastern Yucatan Peninsula, now indicating that cultivation occurred between 5.6-4 kyr cal. BP. Whilst Ambergris Caye is a modern Belizean island, it is a geographical extension of the Yucatan Peninsula and therefore represents the new baseline for cultivation in the eastern Yucatan Peninsula (~4.6 kyr cal. BP). The early finding for cultivation in Ambergris Caye reflects the

systematic issue associated with the low number of investigations into ancient Maya land-use in the dry forest ecosystems, with potential older records available from unexamined sites. As Archaic settlers frequently moved around the Yucatan Peninsula, rather than permanently settling, potentially the evidence for early cultivation exists in locations that show no evidence for permanent settlements. Both the Laguna Esmeralda and Basil Jones records show that these environments were important ecosystems for early inhabitants, with the rich soils and diverse plants providing resources for subsistence.

The finding for Archaic cultivation on Ambergris Caye represents an important example to understand the extent to which dry forests influenced cultivation strategies. It is currently unknown how the early inhabitants of Ambergris Caye accessed the island, whether it be from the north (Yucatan) and south (mainland Belize). Evidence for a southern occupation comes from the earliest evidence for settlement on the island (Marco Gonzalez), which has also been hypothesised to have had a trading relationship with the Belizean settlement of Lamanai (Graham *et al.*, 2017). The cultivation episode from Basil Jones predates the occupation of both of these settlements, indicating that this relationship did not drive initial occupation on the island. The ecological similarities between the site of Basil Jones and the mainland Yucatan present an important factor to explain why cultivation predates the archaeological interpretations by more than 2000 years. The numerous small magnitude fire events, immediately preceding the onset of cultivation, has been interpreted to represent an early form of milpa agriculture (Chapter 4), a land-use method used throughout the Yucatan Peninsula for the cultivation in maize. Theoretically, the ecological similarities and evidence for similar land-use methods indicate that the first settlers were from the Yucatan Peninsula by using the Bacalar Chico Canal (located on the north of the island) to access Ambergris Caye. These inferences imply that the dry forest ecosystem to have been an important component of what drove early inhabitants to the Ambergris Caye then is currently thought.

7:3:2 Ancient Maya management of economically important species.

Thus far, the ecological management of the dry forest ecosystems by ancient Maya communities has mainly been discussed through the lens of cultivation strategies despite the dry forest ecosystem proving a range of economically important species to be used by the communities. One of these economically important species, *Brosimum alicastrum*, is argued here to have been managed by the ancient Maya around the Laguna Esmeralda catchment (Figure 5.5), as percentages of the taxa show increasing values closely

associated with periods of increasing ancient Maya activity in the environment. *Brosimum alicastrum* has been largely discussed as an economically important species for the ancient Maya, as its fruit provided subsistence and the tree provided shade (Ford, 2008; Ford *et al.*, 2015). Palaeoecological evidence for the management of economically important species by the ancient Maya is largely limited to two site examples, showing the management of pine/palm from Lamanai (Rushton, Metcalfe and Whitney, 2012) along with pine from Copan (McNeil *et al*., 2010; McNeil, 2012)

The scope of these management strategies from Copan and Lamanai were aided by archaeological evidence showing that the taxa were used for construction. The management of *Brosimum* is not grounded in archaeological evidence and therefore remains difficult to contextualise the extent to which this taxon was used by the ancient Maya. However, this finding does highlight how palaeoecological records can use anomalous changes in taxa concentrations to determine if these species were managed by the ancient Maya. Palaeoecological records are often omitted from research scopes that aim to understand the management of economically important species (Ford, 2008, 2015), due to the low taxonomic resolutions of pollen identified. However, this research, along with the previously mentioned investigations, highlight the value of palaeoecological records to understanding this method of land-use by showing that variations in ecological taxa may reflect the management of these species by the ancient Maya, indicating a diverse method of land-use that did not strictly focus and rely on maize.

7:3:3 Use of freshwater resources

The sinkhole at Basil Jones and the lakes of Lake Chichancanab and Laguna Esmeralda represent important freshwater resources in the respective regions. Based on the palaeoecological evidence, changes in the dry forest along with the appearance of cultivation is also argued here to show the importance of these freshwater resources for the inhabitants of the respective regions. These periods of land-use are particularly evident when compared to regional palaeoclimate records that show a strong correlation between ancient Maya management of the dry forest ecosystem and drought events.

From an ancient Maya perspective, small sinkholes, such as the one at Basil Jones, have been interpreted to represent a local source of freshwater for small communities and hold no degree of political ownership (Wyatt, 2014). In contrast, larger sinkholes, such as the ones around the regional capital of Chichen Itza, show evidence that these larger water resources were ritually important for the larger political capitals of the ancient Maya

(Lucero, 2002; Iannone, 2014). Currently, there are no examples of ownership of lakes such as Lake Chichancanab or Laguna Esmeralda. Archaeological evidence has yet to indicate if the sinkhole at Basil Jones was ritually important for the island inhabitants and therefore the degree of ownership of the resource cannot yet be established. Archaeologists have argued that standing water resources were often used as a form of management for crop cultivation (Kunen, 2001), with pots used to water the crops grown locally. From the Basil Jones perspective, this form of "pot agriculture" (Hoggarth, *personal communication*), potentially shows how the dry forest ecosystem on the island was managed, acting as part of a communal landscape for coastline inhabitants to practice mixed subsistence strategies. Similar processes were also achievable on the mainland, with the lakes of Chichancanab and Esmeralda providing water to aid in the management maize.

Along with the water resources aiding in the management of maize in the regions discussed, a combination of palaeoclimate (Hodell *et al.*, 1995; Webster *et al.*, 2007; Kennett, *et al.*, 2012; Pollock *et al.*, 2016) and palaeoecological records (Chapter 4-5) (Leyden, 2002), demonstrates that all regions in this research were used in response to drought conditions (Figure 7.2). From the Basil Jones record (Figure 4.5) and the Lake Chichancanab (Figure 6.9) reinterpretation, evidence for the cultivation of *Zea mays* during the Preclassic abandonment period (*ca* 200-250 CE). This period is closely associated with southern lowland records of a period of drought (Hodell, 2007; Webster, 2007; Medina-Elizalde, 2016). Whether these activities symbolise localised communal activities or a political response, where polities maximised all water resources in the ancient Maya version of jurisdiction, it indicates that the freshwater resources were likely important locations for crop management during this period of drought. Recent investigations have shown that at approximately 5.5 kyr cal. BP the climate was increasingly dry on the mainland Yucatan Peninsula (Serrato Marks *et al.*, 2020). As this strongly correlates with the finding of maize cultivation at Laguna Esmeralda, ca 5.6 kyr cal. BP, potentially this form of landscape management (use of water resources), were particularly favourable in the drying Archaic climate

The next period of land-use during drought conditions highlight the different components of land-use explained, through crop cultivation at some sites and increasing fire management at another. The Laguna Esmeralda and Lake Chichancanab records have both been discussed previously regarding the period of land-use during the Terminal Classic (Chapter 5-6), showing that two freshwater resources were cultivated during a time of intensive drought. From Basil Jones, evidence for cultivation is found during the

Postclassic, but an intensive period of forest reduction and a high-magnitude fire event during the Terminal Classic is interpreted here to indicate management of the dry forest ecosystem (Figure 7.2). Whilst natural causes of the fire event cannot be completely ruled out during the Terminal Classic, with drought amplifying the fire signal, it has been widely discussed that fire is not a natural component of seasonally dry forest ecosystems (section 2:4:4) and therefore concluded that anthropogenic activities were the root cause of this fire event (Chapter 4). During this high magnitude fire event, the declines in Moraceae/Urticaceae highlight the largest period of forest reduction, over a short period, in the Basil Jones record. This is comparable to the Laguna Esmeralda record, were the rapid reduction of Moraceae/Urticaceae is recorded alongside evidence for maize cultivation. These anthropogenic indicators are interpreted here to reflect the management of the dry forest ecosystem in response to the increasing need for freshwater resources. From the Laguna Esmeralda and Lake Chichancanab perspective, the Terminal Classic is the only period will cultivation appears in both catchments, indicating a growing intensification of subsistence around freshwater resources. At Basil Jones, the high magnitude fire event highlights how the dry forest ecosystem was managed, to clear large parts of the forest to improve access to the freshwater resource.

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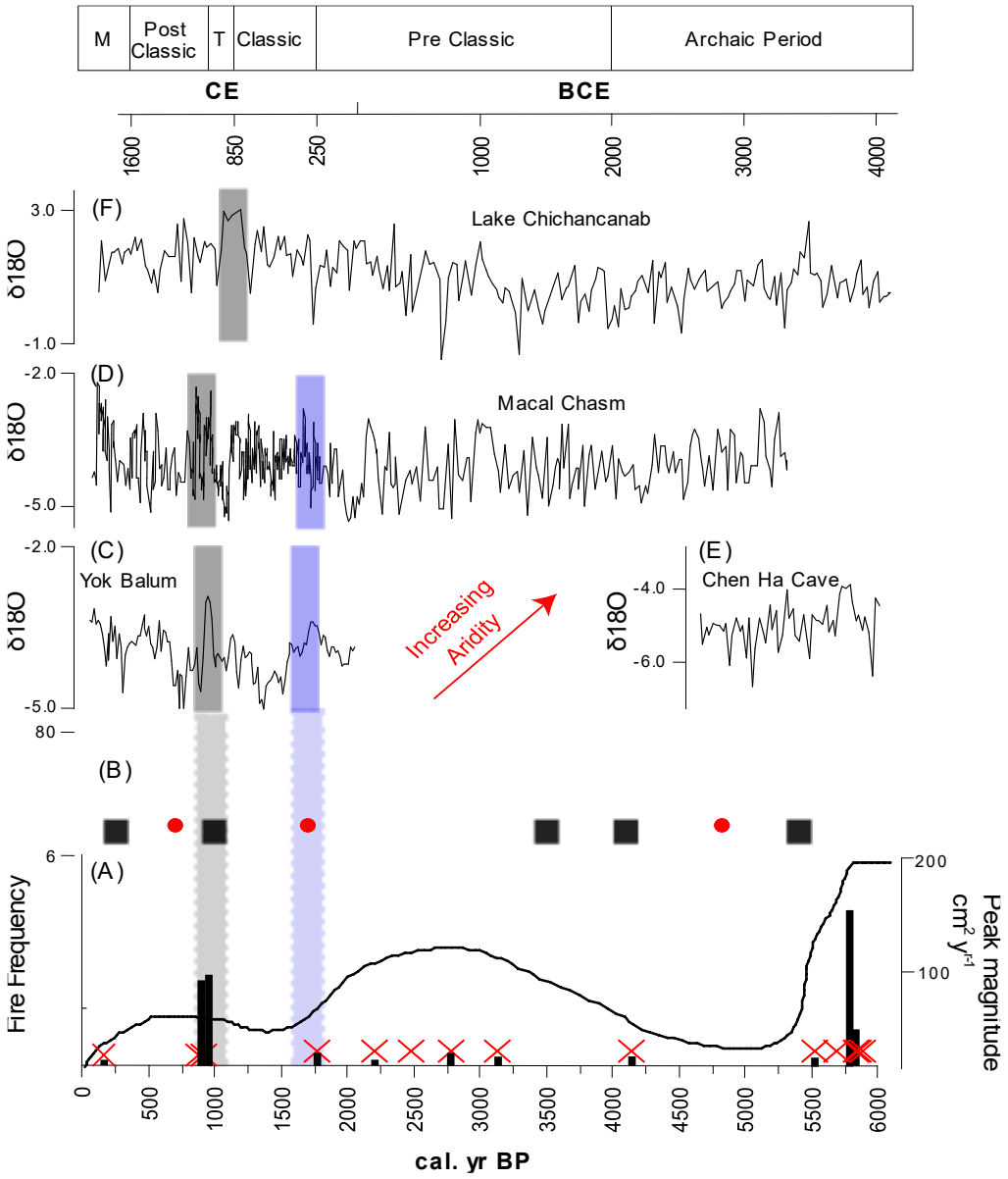


Figure 7.2

Diagram of palaeoecological records from Basil Jones and Laguna Esmeralda and associated palaeoclimate record. Top shows Illustration of the important ancient Maya Periods, C= Classic, P. Classic = Postclassic. Terminal Classic Drought (TCD) (ca 750-1100 CE) and Preclassic Abandonment (ca 150-250 CE) are highlighted. (A) Indicates the fire frequency, peak magnitude and peak occurrence from the Basil Jones record. (B) indicates the presence of Zea mays from Laguna Esmeralda (■) and Basil Jones(●). Grey and blue boxes indicate the periods of drought associated with the Terminal Classic (grey) and Preclassic (blue) drought periods. Oxygen isotope (^{18}O) are shown from regional archives. Speleothem record from Yok Balum (C)(Kennett et al., 2012), Macal Chasm (D) (Webster et al., 2007) and Chen Ha Cave (E) (Pollock et al., 2016), with the lake record from Lake Chichancanab (F)(Hodell, Curtis and Brenner, 1995) also shown.

7:4 Conclusions

The central aim of this thesis was to understand ancient Maya land-use strategies from lower-density settlements. As palaeoecological methods from higher density settlements have been used to support narratives that associate ancient Maya activities as environmentally degrading, making them appealing to 21st-century audiences, smaller density settlements represent a crucial step in developing an understanding for the variability of these activities. As both records presented in this thesis are dominated by seasonally dry tropical forests, insights into how the ancient Maya managed these ecosystems represent important considerations for modern conservation strategies. As seasonally dry tropical forests are important agricultural landscapes in the modern tropics, with methods of land-use mimicking an intensified version of ancient Maya *milpa* agriculture, understanding how past societies interacted with these environments is pivotal for directing how these ecosystems will be sustainably managed in the future. The key findings from this investigation are as followed:

The Yucatan Peninsula represents the earliest palaeoecological evidence for Zea mays cultivation

As palaeoecological evidence represents a crucial tool in understanding when cultivation spread throughout the Americas, this research has shown that the Yucatan Peninsula represents a key area of interest for the initial development of *Zea mays* cultivation. The finding of *Zea mays* on the mainland (*ca* 5.5 kyr cal. BP) and the island (*ca* 4.8 kyr cal. BP) highlights the value of investigation sediments in locations void of large settlements, with older evidence likely available in the region becomes a focus for research. The seasonally dry tropical forest ecosystems of the Yucatan are argued here to be a key driver for the development of cultivation, in the lowlands, as the deep fertile soils and adaptations to prolonged drying periods presented unique ecological conditions for the sustainable management of *Zea mays.*

The finding of *Zea mays* at Laguna Esmerlada from this thesis can be compared temporally to recent discoveries in South America, regarding the first detectable presence of agriculture. Lombardo *et al*., (2020) shows signals for squash being cultivated in Bolovia at around 10.2 Kyr cal. BP and *Zea mays* adapted around 7 Kyr cal. BP. In the Ecuadorian Amazon, *Zea mays* is found from pytholiths and pollen evidence at approximately 5.5 Kyr cal. BP. These findings for *Zea* cultivation, both *mays* and other variants (Kistler *et al.*,

2018) throughout Central and South America shows that once the plant was originally domesticated, it rapidly spread throughout the regions. Likely these dates represent an important period of agriculutal development by pre-hispanic peoples, but with more research and increasing number of sites analysed, this date may be pushed further back.

Island sites as a climate refuge

The findings of cultivation correlating with drought, social instability (*ca* 150-250 CE) and consumption of maize on the south of the island of Ambergris Caye (Graham *et al.*, 2017), demonstrates that the northern dry forest had an important role in ancient Maya subsistence strategies. As the maize grain found falls within the range of dates associated with the Preclassic abandonment period, it is argued that the maize found in Marco Gonzalez was likely sourced from the northern dry forest ecosystem. The consistent use of marine resources and now detected increasing use of terrestrial resources during periods of drought/social instability has been used as the basis to argue that the island of Ambergris Caye acted as a climate refugee for the ancient Maya. Not only does this add another lens for questioning how the ancient Maya responded to periods of drought but also demonstrates that island sites had greater importance for the wider ancient Maya than previously thought.

The spatial variability of ancient Maya land-use is evident at a local scale

The low spatial resolution of palaeoecological records across the ancient Maya region has resulted in the extrapolation of results to make inferences regarding the extent of environmental impact associated with ancient Maya activities. The spatial variability of these activities is high, as demonstrated from the interpretations from Lake Chichancanab and Laguna Esmeralda. As two adjacent lake systems clearly show altering patterns of land-use throughout ancient Maya occupancy, careful considerations must be made single records can be used to extrapolate interpretations of environmental impact, even on a local scale.

This concept of the spatial heterogeneity of lake records is not strictly limited to the Central American region, but also extends to the Amazonian region, where nearby lakes reflect contrasting pollen records regarding pre-colonial landscape management (McMichael *et al*., 2012; Bush *et al*., 2007)

Terminal Classic drought drove the ancient Maya to intensify strategies around water resources

The complicated relationship between the ancient Maya and drought events is particularly demonstrated in the Terminal Classic (*ca* 750-1100 CE), were archaeological evidence indicates a climate-driven collapse of major centres around the region (Gill *et al.*, 2007; Iannone, 2014; Hoggarth *et al.*, 2016). The palaeoecological evidence from both Basil Jones, Laguna Esmeralda and Lake Chichancanab show methods of land-use during this drought, with intensified forest clearance recorded around the sites developed in this research (Basil Jones, Laguna Esmeralda). Whilst it cannot yet be established if these were the response of local small populations or political response to wider control of water systems, the records demonstrate that the Terminal Classic drought event drove the ancient Maya to intensify land-use around these resources to a scale not recorded previously.

Palaeoecological records demonstrating value to ethnobotany

The use of pollen as a method for understanding ancient Maya forest management has been largely discounted by leaders in ethnobotany, due to the low taxonomic resolution achieved through pollen identification (Ford, 2008; Ford and Nigh, 2015). Palaeoecological records provide a crucial temporal perspective for ecological change, something which is not obtainable through modern observations of the forests. Whilst the taxonomic resolution remains an underlying issue, records have demonstrated that the methods employed in this thesis and elsewhere studies (McNeil *et al.*, 2010; Rushton, Metcalfe and Whitney, 2012) can aid in the interpretations of how the ancient Maya managed the forests.

This idea of a highly spatially organised landscape is beginning to be uncovered as researchers continuously reflect how modern forests reflect past-land-use strategies of the ancient Maya (Ford, 2008; 2012). The use of economically important species, ranging from *Pinus* for building material (Rushton, 2012) to *Piscidia* for fuel (Dussol *et al*., 2020) are beginning to be found in the palaeo records, further supporting the use of such proxies for identifying complex patterns of land-use, through the management of economically important species.

The deterministic ancient Maya and dating the Anthropocene

The beginning of this thesis discussed important themes in pre-historic land-use studies such as the dating of the Anthropocene. This thesis has highlighted the values of

investigating the lower density settlements of Central America and have provided robust dating regarding the onset of cultivation in the respective areas. Whilst these appearances of cultivation does not represent new markers of the Anthropocene they highlight how new horizons of human activity can be found in unlikely settlements. By investigating at a higher spatial resolution throughout Central America, and likely South America, fingerprints of human activity will continue to be pushed back improving the resolution of when important transitions (e.g. first cultivation of maize) of human land-use occurred.

One of the key themes of this thesis was regarding the link between environmental deterministic thinking and how it fed into narratives regarding the ecological sensibility of the ancient Maya. As long-term exploitation models have represented a key theme in environmental deterministic views of ancient Maya land-use (Shaw, 2003; Diamond, 2005), land-use from lower-density settlements do not detect evidence for continued, long-term, environmental degradation. Throughout periods of cultivation and fire use in the palaeoecological records, both Laguna Esmeralda and Basil Jones show little impact on primary forest vegetation, bar the intensification of land-use during the Terminal-Postclassic eras. This demonstrates that the growth of these smaller density settlements did not result in serious environmental impact, with small scale cultivation likely a feature of the subsistence strategies. As a result, narratives that continue to determine the relationship between an entire civilisation and their environment off one record of deforestation need to examine further the range of activities associated with the civilisation. This thesis provided one minimal impact model for ancient Maya land-use, as the Coba record (Leyden, 2002) provided one maximum impact model. The likelihood at this time is that the ancient Maya participated in a range of activities, potentially intensifying around the urban centres, with minimal impacts recorded in the peripheral, lower density settlements.

7.5: Future Goals and Challenges

Thus far, this chapter has attempted to answer key questions regarding ancient Maya land-use in the seasonally dry tropical forest ecosystems of the Yucatan Peninsula. Lower density settlements were chosen as the scope of this investigation as they were under-represented in the palaeoenvironmental research regarding ancient Maya land-use strategies. This research has attempted to show the benefits of cross-disciplinary research from the fields of archaeology and palaeoecology by showing the value of the respective disciplines in informing our wider understanding of the ancient Maya civilisation. Land-use strategies represent a complex process which involves numerous dynamics, with

palaeoecological interpretations framing the ecological principles of these activities. From this research, key avenues can be addressed to better inform, strengthen and move forward the understanding of ancient Maya land-use.

Ancient Maya impact on forest cover represented an important theme in this research, with Chapter 6 highlighting how valuable modern environmental data can be for interpreting palaeoecological records. It has been argued that there is a lack of available information regarding catchment properties (size, coring location) from numerous investigations attempting to contextualise ancient Maya land-use, with smaller coring locations particularly lacking these kinds of measurements, making inter-site comparisons difficult. Future work could attempt to categorise these records throughout the highlands and lowlands, making obtaining key information more accessible for researchers. Lake Coba represents an interesting narrative regarding how lake properties, and how the local environment may influence palaeoecological interpretations. A series of surface samples should be analysed from this lake system and measured to modern forest cover to determine if the scales of deforestation recorded are comparable to the modern landscape. If it can be proven that the large temple site in proximity to the lake is influencing the palaeoecological signal then future work can attempt to reconstruct past forest cover through computational methods, which investigate the influence of spatial clearances on changes in arboreal pollen (Bunting *et al.*, 2004; Hellman, Bunting and Gaillard, 2009). As Lake Coba represents an important example for the influence ancient Maya constructions would have on palaeoecological interpretations, future work aiming to improve interpretations of forest cover from other records can follow, dependent on the findings.

As the record from Laguna Esmeralda represents one of the earliest palaeoecological evidence for *Zea mays* in the Maya Lowlands (*ca* 5.6 kyr cal, BP), a more robust chronology for this horizon would provide a more precise time for when this period of activity occurred. Similarly, comparisons between Laguna Esmeralda and Lake Chichancanab were limited due to the chronological baseline of the Chichancanab core. The palaeoecological record indicates that cultivation was evident at Laguna Esmeralda during the Preclassic, but it is currently unknown if such activities were present at Chichancanab. By obtaining a longer core, many of which already exist and have been used for palaeoclimate reconstructions, a greater understanding of how land-use differed between Laguna Esmeralda and Lake Chichancanab can be obtained. Questions regarding shifting cultivation between the lakes can be addressed by analysing palaeoecological records from Lake Chichancanab, whilst also understanding if the lake was cultivated

during the Archaic, similar to Laguna Esmeralda. Another interesting record potentially obtainable would be from the archaeological site known as Yo'okop in northern Quintana Roo. A hypothesis has been made regarding the cultural decline of the site of Yo'okop, with archaeological interpretation suggesting the sinkhole within the archaeological site dried up during the Terminal Classic (*ca* 1000 CE) (Shaw, 2000; Sanchez, 2015). A palaeoenvironmental record from this sinkhole could better indicate the hydrological conditions of this sinkhole during these drought events with a palaeoecological investigating local land-use around the sinkhole. These investigations would better inform our understanding for the management of water resources during periods of drought, with a comparison between the records here and Yo'okop allowing for an additional understanding regarding water management between higher and lower density settlements.

The island of Ambergris Caye offers many opportunities to advance our understanding of the land-use strategies of the ancient Maya. The record presented in this thesis represents the first palaeoecological investigation that focuses on ancient Maya land-use on an island site. By completing this analysis, this research has rewritten how islands are viewed regarding ancient Maya land-use. However, one of the key questions yet to be answered regards how occupation first initiated on the island. This research hypothesised that the migrants likely came from the northern Yucatan, where similar ecological conditions pulled inhabitants towards the site of Basil Jones, where it was managed for subsistence. There remains a lack of understanding for how subsistence was maintained on the island, with marine resources the primary source of nourishment. Potentially the link between the southern site of Marco Gonzalez and the Belizean site of Lamanai points to a Belizean origin of occupation. Future research would attempt a palaeoecological reconstruction from Marco Gonzalez and other coastline settlements to determine if land-use activities, such as the use of fire, were methods used by the ancient Maya.

Finally, one of the fundamental challenges of palaeoecological research regards the temporal perspective. The resolution of analysis coarsely covers numerous periods associated with the ancient Maya. By finding catchments with higher sedimentation rates, a higher temporal resolution of ecological change can be assessed. Since the sedimentation rates are rarely known about lake systems in the tropics and not acquired until later in the research project. If a higher temporal resolution for the pollen sampling can be obtained, potentially 50-100 years, it would improve the understanding of short-term ecological change associated with ancient Maya land-use. These types of investigations would require a strong chronological framework to tightly constrain patterns of land-use to climate

drying/political decline. By gathering this information though, a clearer picture regarding the intensity and methods of ancient Maya land-use can be completed strategies and methods of ancient Maya land-use can be completed.

Appendix A

Methodological details used in this research

Throughout this thesis, numerous additional routines were completed to ensure the correct measures were taken when addressing a statistical problem. Various parameters could have been chosen for both the methods of pollen zonation and the CHARanalysis protocol. These were important decisions to be made and therefore rigorous methods were employed to ensure a robust and reproducible method were chosen. Along with these decisions, additional statistical information that was not shown in the main body of the thesis (pollen confidence intervals; DCA analysis) are included here.

Table A.1 Detailed breakdown of the number of pollen grain counted per sample for the Basil Jones and Laguna Esmeralda cores, along with the total sums for the surface samples.

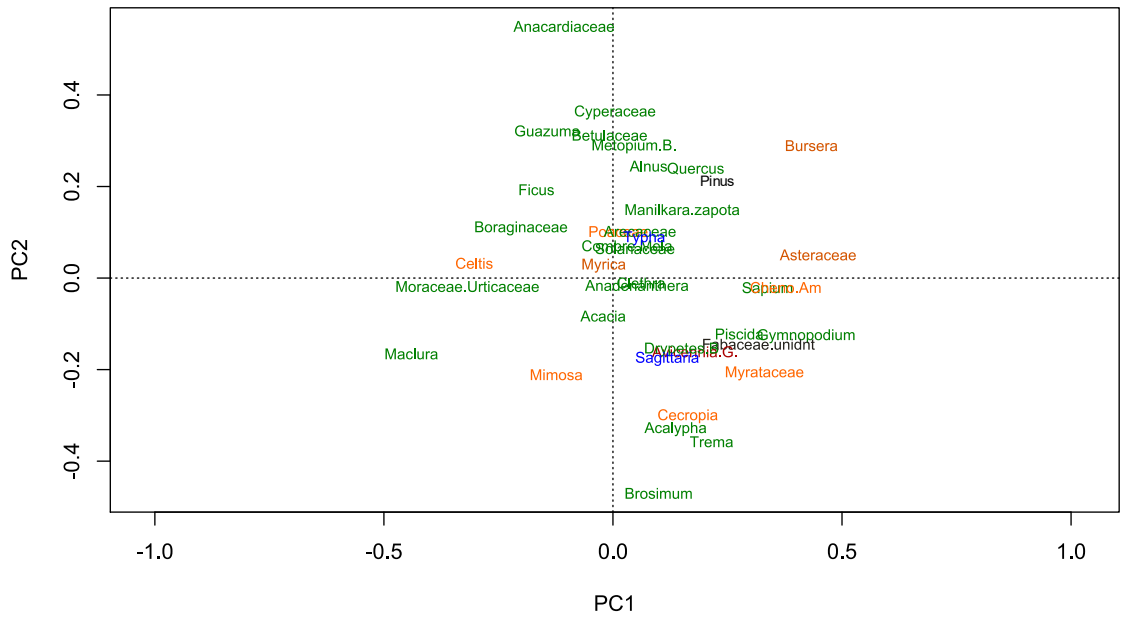
Basil Jones		**Laguna Esmeralda**		**Surface Samples**	
Sample depth(mc)	*Number of pollen counted*	*Sample depth(cm.master depth sequence)*	*Number of pollen counted*	*Sample name*	*Number of pollen counted*
0	200	**6.5**	275	**ESM1**	153
20	315	**16**	289	**ESM2**	157
40	303	**26**	292	**ESM3**	150
60	205	**36**	304	**ESM4**	150
70	208	**38**	202	**ESM6**	150
78	313	**40**	200	**ESM8**	152
80	291	**42**	206	**CHICH1**	176
82	305	**44**	211	**CHICH2**	152
90	200	**46**	267	**CHICH4**	153
100	215	**58**	270	**CHICH5**	150
110	200	**60**	200	**CHICH6**	162
120	240	**66.5**	258		
125	301	**76.5**	284		
130	301	**96.5**	310		
135	206	**107**	307		
141	250	**117**	300		
150	305	**127**	300		
160	301	**137**	254		
170	274	**147**	294		
185	202	**167**	201		

190	211	**177**	224		
200	260	**197**	209		
220	217	**207**	257		
260	300	**216.5**	300		
280	300	**227.5**	300		
300	275	**236.5**	278		
320	297	**247.5**	300		
340	200	**267.5**	300		
		276.5	300		
		287.5	300		
		297.5	308		
		313	310		
		322.5	231		
		333.5	245		
		343	205		

PCA plots for vegetation groupings

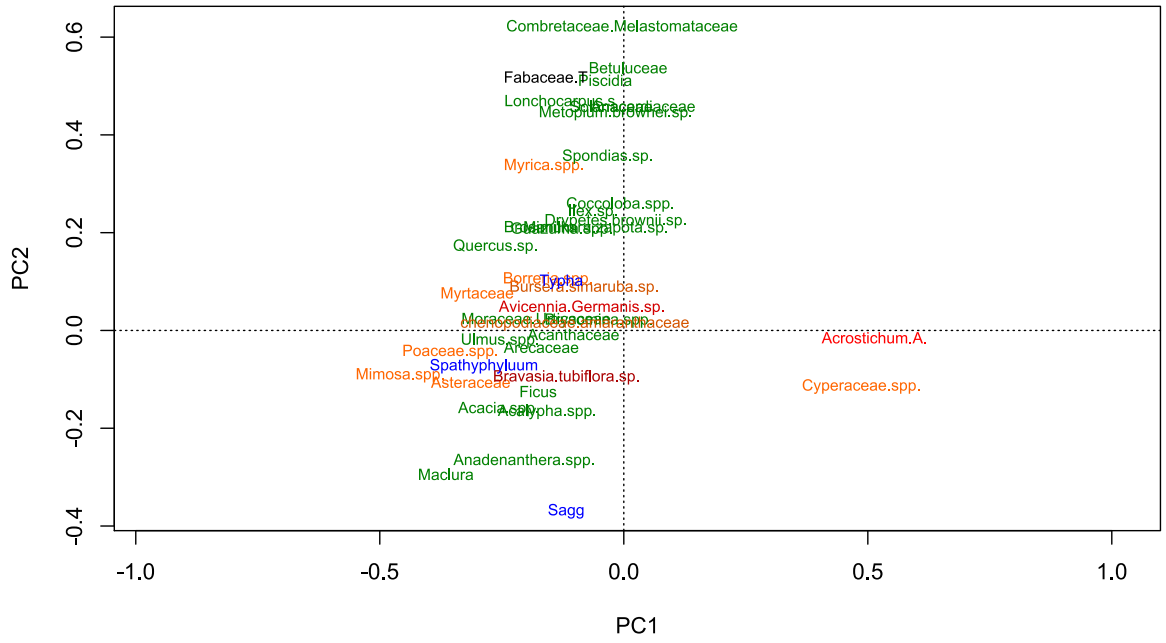
For this thesis, PCA plots for the Laguna Esmeralda and Basil Jones core were completed to aid with the groupings of the vegetation. To perform the PCA analysis, taxa had to have at least 2% abundance in a minimum of 2 samples or were continuous in low abundances for at least 5 samples. Pollen data were transformed via Hellinger transformation in a similar protocol as explained with the surface samples in Chapter 3. Taxa such as *Pinus* and Fabaceae were not grouped directly due to low taxonomic resolution for the latter and long-distance transportation of the pollen grains for the former.

Laguna Esmeralda



Appendix Figure A.1 PCA plot for the Laguna Esmeralda core. Colours indicate the vegetation groupings with green (forest vegetation), orange (openness/disturbance indicators), blue (aquatic) vegetation, red(mangrove vegetation) and black the vegetation that is difficult to directly classify (Pinus because of long-distance transportation and Fabaceae due to the low taxonomic resolution)

Basil Jones



Appendix Figure A.2 PCA Diagram for the Basil Jones Core. Colours indicate the ecological groupings assigned with green (forest vegetation), orange (openness/disturbance indicators), blue (aquatic) vegetation, red(mangrove vegetation) and black the vegetation that is difficult to directly classify (Pinus because of long-distance transportation and Fabaceae due to the low taxonomic resolution)

Protocol for selecting the method for pollen zonation

To choose the appropriate method for pollen zonation in this thesis, a series of tests were performed within the Psimpoll programme (Bennett, 2005). Each method of zoning and pollen transformation was tested individually to determine **(a)** The number of zones detected under the various combinations of method and transformation; **(b)** Zones which appeared consistently throughout all methods. Based on the results of this testing, the method of zoning was chosen. The methods were then finally tested to understand their sensitivity to the inclusion of low percentage data. The threshold for the inclusion of taxa percentage was changed from 5% inclusion to 0.5% to determine if the inclusion of additional data would change the location of the zones. Figure A.3 shows a hypothetical work output following this methodology.

Protocol for selecting parameters for CHARanalysis

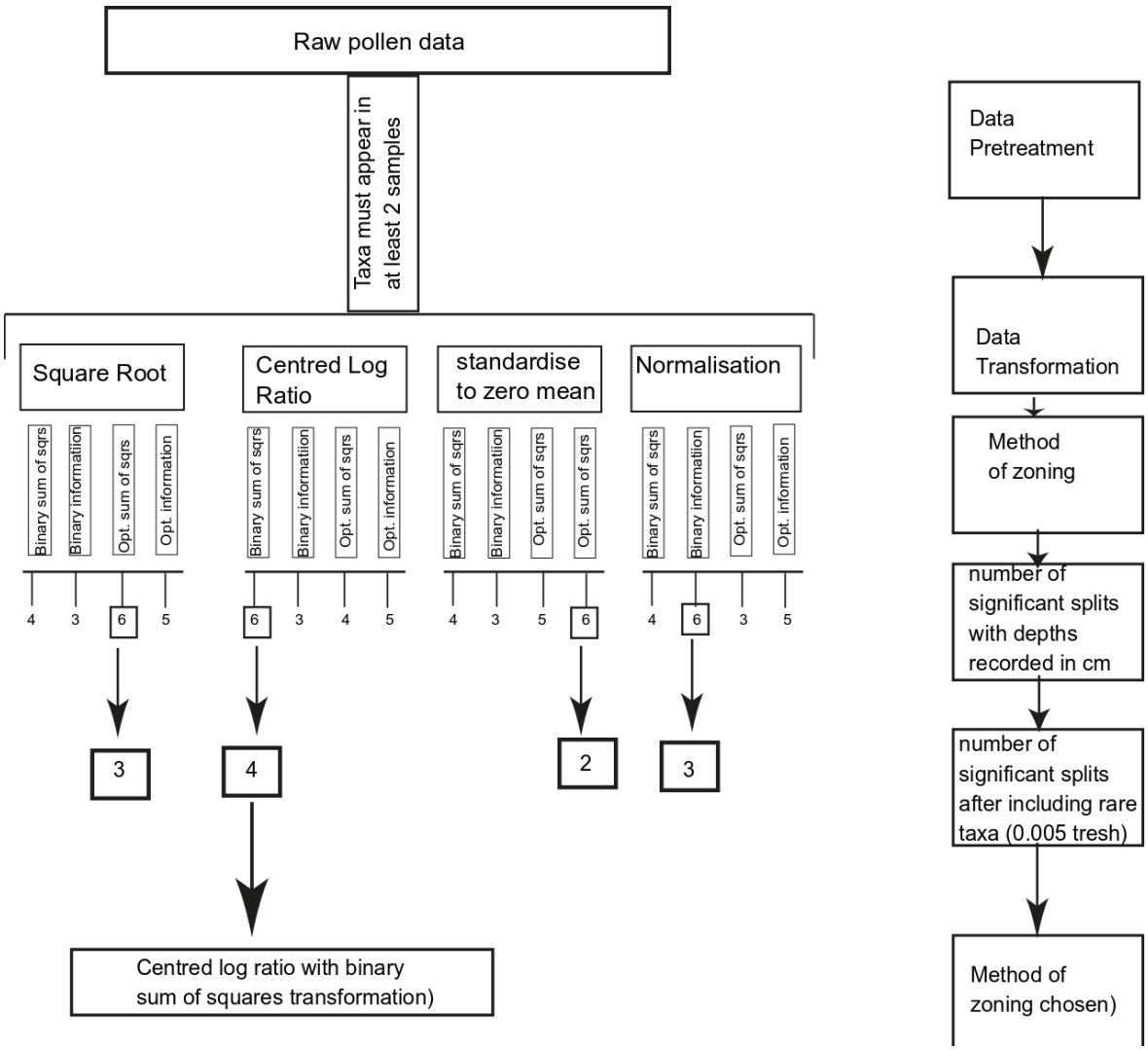
To determine the most appropriate parameters to run the CHARanalysis methodology, all possible variables were tested to analyse the sensitivity of the record to changes in the parameters. Both the smoothing window and the fire frequency window were tested every 200 years, between 400-1200 years. Each method for charcoal transformation (No

transformation, Base-log transformation, natural log transformation) were tested. Each variable was also tested for the method of smoothing (Lowess, Lowess robust to outliers, moving median, moving mode, moving mean). The number of windows produced per analysis, for each of the variables, were then assessed to determine the number of outputs which produced a signal to noise >3 and goodness of fit (G.O.F) >0.90. (Figure A.4). With these results, percentages were calculated based on how many windows had SNI >3 and G.O.F >0.9 and both SNI >3 and G.O.F >0.9. Table A.1 shows an example of the routine that was tested for all parameters but only shows the one used in the final analysis for the Basil Jones core. Figure A-2 showing an example of the windows output from the CHARanalysis.

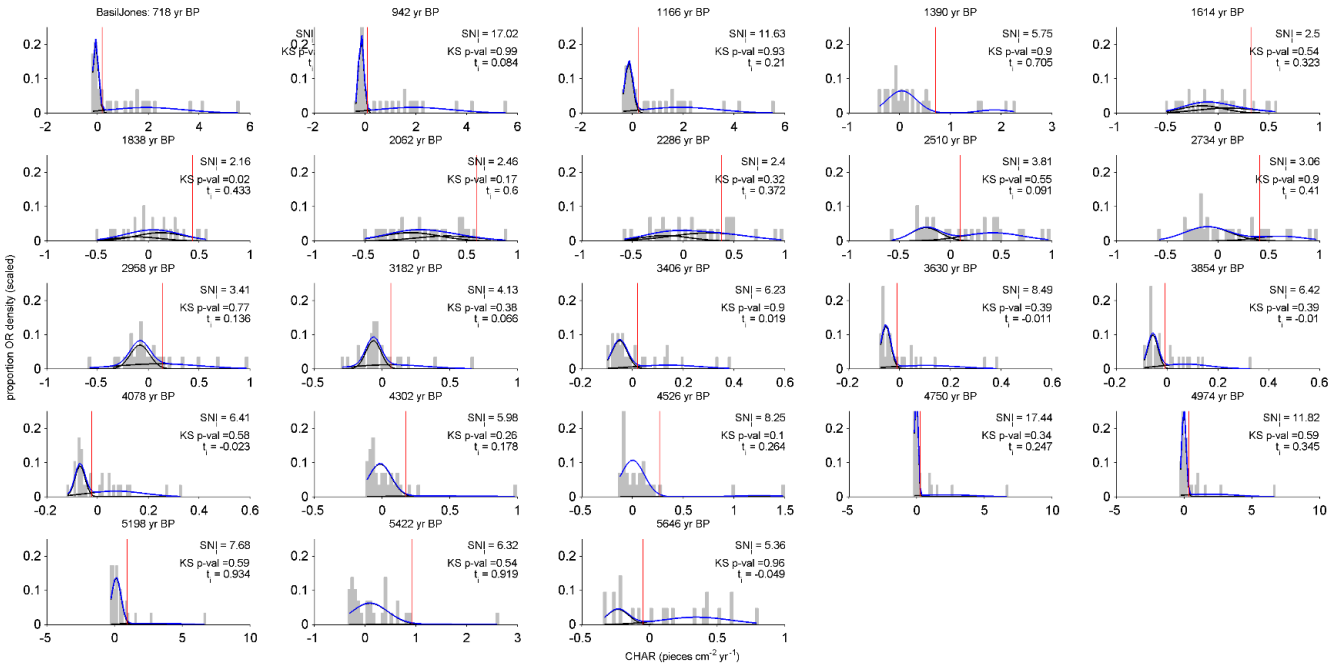
Table A.2 Protocol employed to arrive at the selected parameters for the Basil Jones core. Only results used in the final selection are shown, but all other methods of transformation and methods of smoothing were completed to arrive at this decision. Highlighted column shows the important results from the steps

Basil Jones CHARanalysis					
Smoothing window	400	600	800	1000	1200
number of windows produced	24	23	22	22	22
No data transformation					
Windows with SNI >3	16	16	18	17	17
Windows with G.O.F =>0.90	5	7	2	6	0
Windows with Both SNI +G.O.F	4	3	6	2	0
Mean of windows no transformation					
SNI (windows with SNI >3/no.of windows)			78.26		
G.O.F(windows with G.O.F >0.9/no.of windows)			26.09		
Both (windows with both SNI>3 and G.O.F >0.9/no.of windows)			26.09		
Smoothing options					
Lowess robust to outliers					
Windows with SNI >3	16	16	18	17	17

Windows with G.O.F =>0.90	5	7	6	2	0
Windows with both SNI + G.O.F	4	3	6	2	0
Mean lowest robust to outliers					
SNI (windows with SNI >3/no.of windows)			78.26		
G.O.F (windows with G.O.F >0.9/no.of windows)			26.08		
Both (windows with both SNI>3 and G.O.F >0.9/no.of windows			26.08		
Method chosen: No transformation and Lowess robust smoothing					



Appendix Figure A.3 Diagram of the work flow for selecting the appropriate zoning method of the long-core pollen analysis. All combinations of variables were used in the Psimpoll software programme.

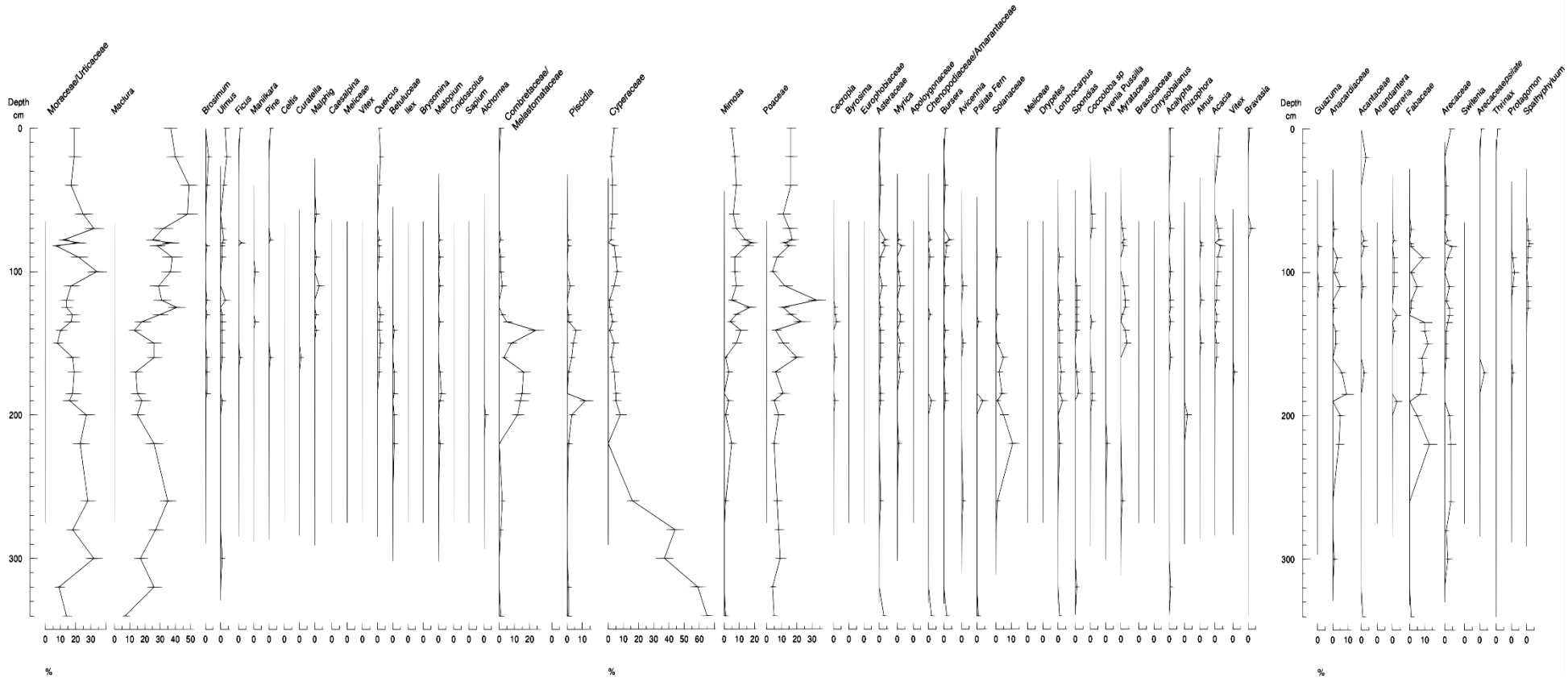


Appendix Figure A.4 Example of the windows produced from the CHARanalysis programme. It was this output that was used to determine how many windows had (a) Signal to noise >3 and (B) Goodness of fit > 0.9 and (c) Both Signal to noise >3 and G.O.F greater than 0.9

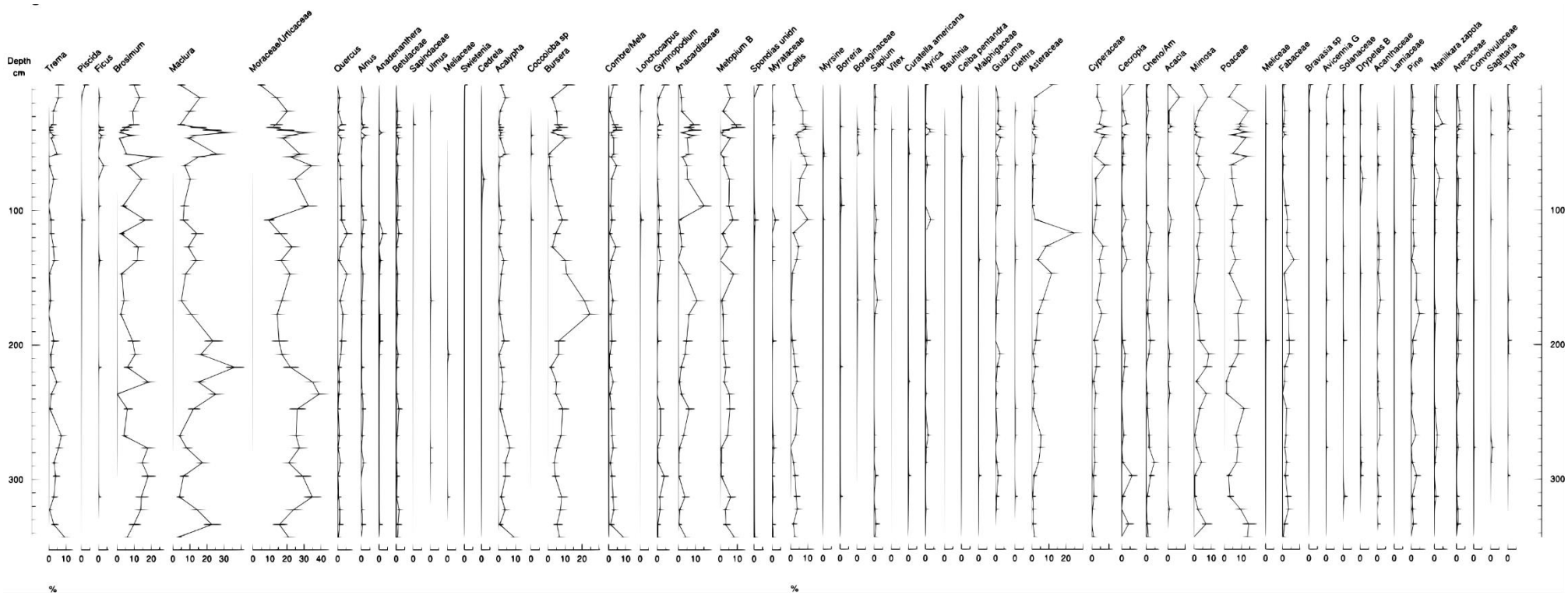
8.1.3 Other statistical outputs

To justify the number of pollen grains counted per samples, 95% percentage confidence intervals were plotted. Upon inspection it was determined that even within this range of confidence, the magnitude of change for taxa was not great enough to warrant additional counting. Figure A-5 to A-8 shows the confidence intervals plotted for Basil Jones, Laguna Esmeralda and the surface sample sediments from Laguna Esmeralda and Lake Chichancanab.

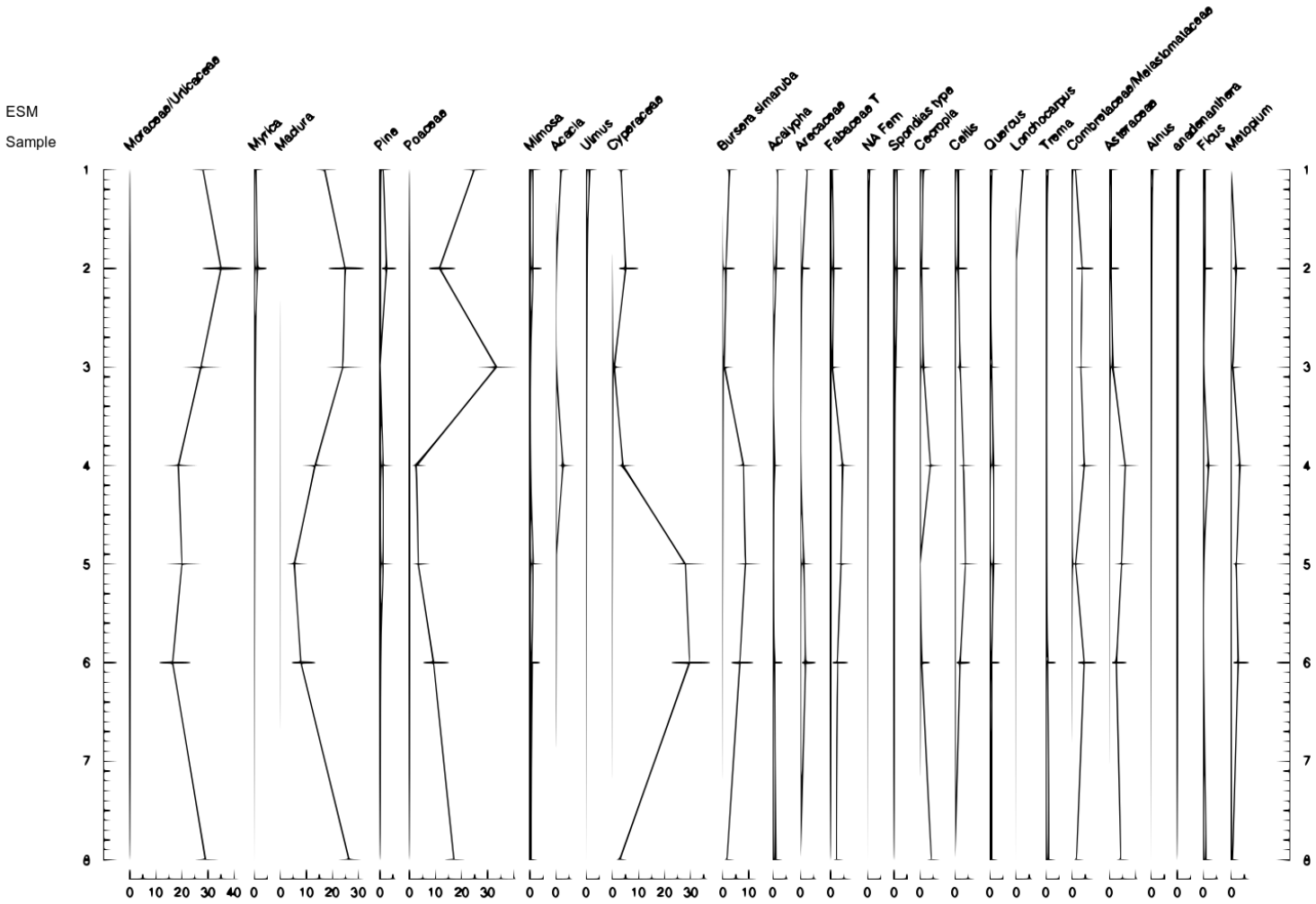
To warrant the use of the Principal component analysis and Redundancy analysis, a detrended correspondence analysis was completed (DCA). From the results, a short environmental gradient is present (Between ± 1). This short gradient warranted the use of PCA and RDA over CCA and CA (Figure A.9).



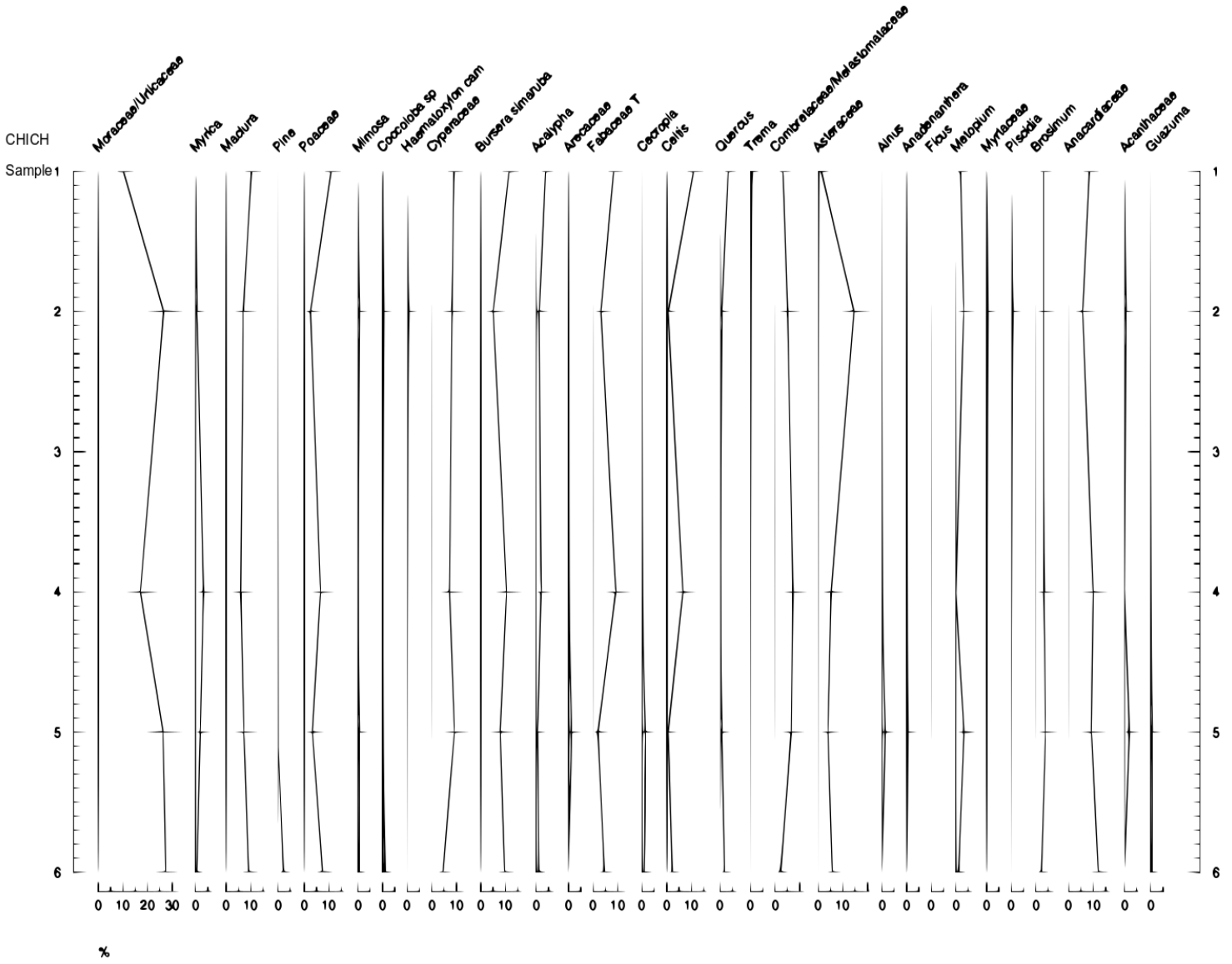
Appendix Figure A.5 95 % confidence intervals for the pollen percentages from the Basil Jones core. Achievable through the Psimpoll programme (Bennett, 2005)



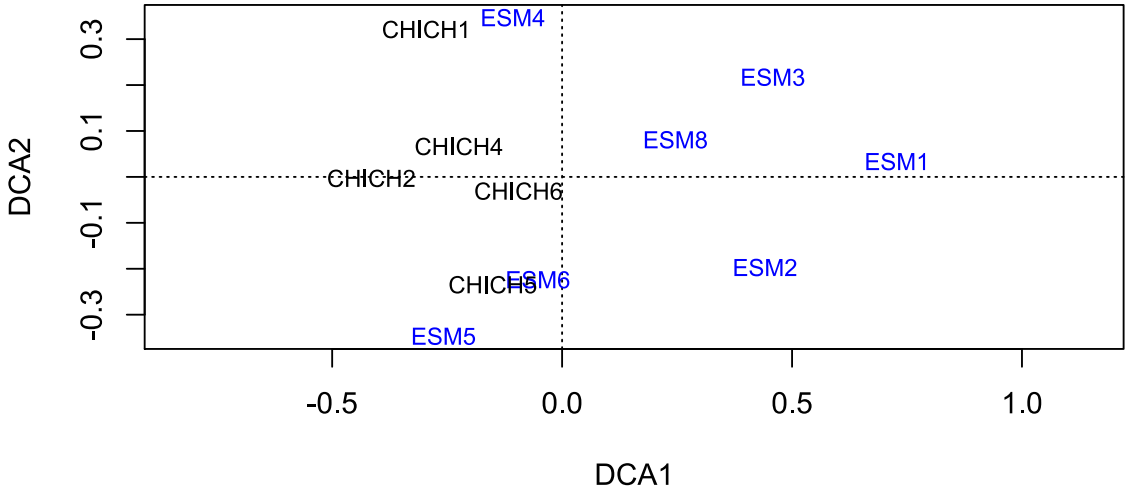
Appendix Figure A.6 95 % confidence intervals for pollen percentages from the Laguna Esmeralda core. Achievable from the Psimpoll programme (Bennett, 2005)



Appendix Figure A.7 95 % confidence intervals for pollen percentages from the Laguna Esmeralda surface samples. Achievable from the Psimpoll programme (Bennett, 2005))



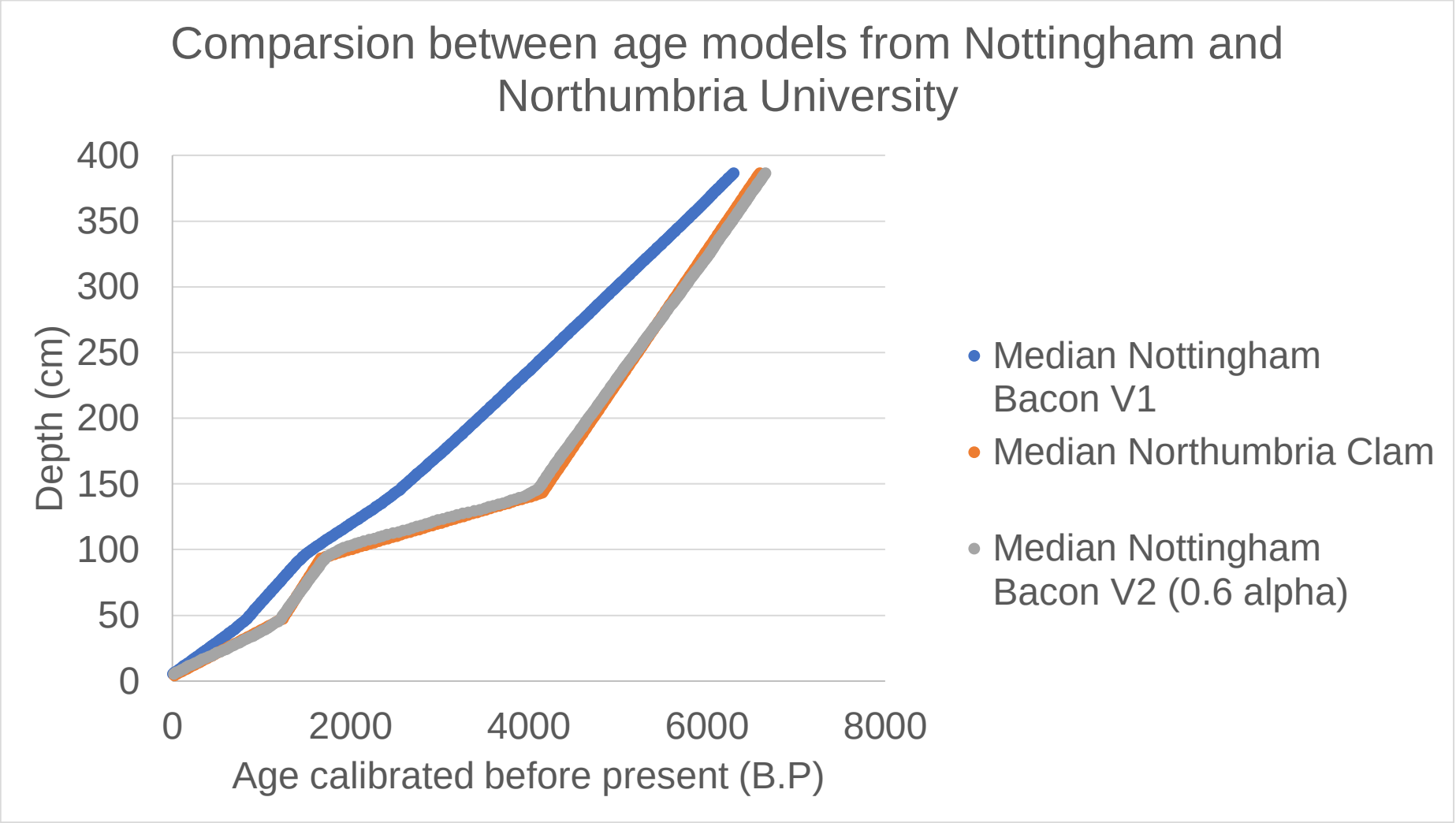
Appendix Figure A.8 95 % confidence intervals for the pollen percentages of the surface samples taken from Lake Chichancanab. Achievable through the Psimpoll programme (Bennett, 2004)



Appendix Figure A.9 Detrended Correspondence Analysis (DCA) for surface samples taken from Laguna Esmeralda (blue) and Lake Chichancanab (black). Short environmental gradient (between -1 and 1) warranted the choice of ordination techniques used in this research

Age model sensitivity for the Esmeralda core

As the Esmeralda core was worked on by researchers from both Nottingham University and Northumbria University, a suitable age model was selected to suit the context of this project. Figure A.10 shows the age model constructed in this thesis compared to the previous one constructed by the colleagues from Nottingham University. The original age model that was produced in bacon (blue) had issues with the date obtained at 144 cm (4101 ± 37 ^{14}C yr BP). With the original alpha rate, bacon attempted to smooth out the sedimentation rate. When the alpha rate was changed to 0.3 in bacon, it produced the second bacon age model (grey). With the adjusted alpha rate from bacon, the age model matched the clam output (orange) produced in this thesis.



Appendix Figure A.10 Age model comparisons between colleagues from Nottingham University and the age model used in this thesis. In order to allow for comparisons between age models in this thesis, the clam age model was selected

Appendix B

“Failure is the condiment that gives success its flavour.”
— Truman Capote

Throughout the course of the PhD research a total of 5 sites were analysed for palaeoecological proxies to gain a better understanding of the spatial heterogeneity of Maya land-use. Of these five, three sites produced reliable data (Basil Jones, Laguna Esmerelda and Lake Chichancanab). For this section, a site that composed almost a year of research for this thesis will be discussed.

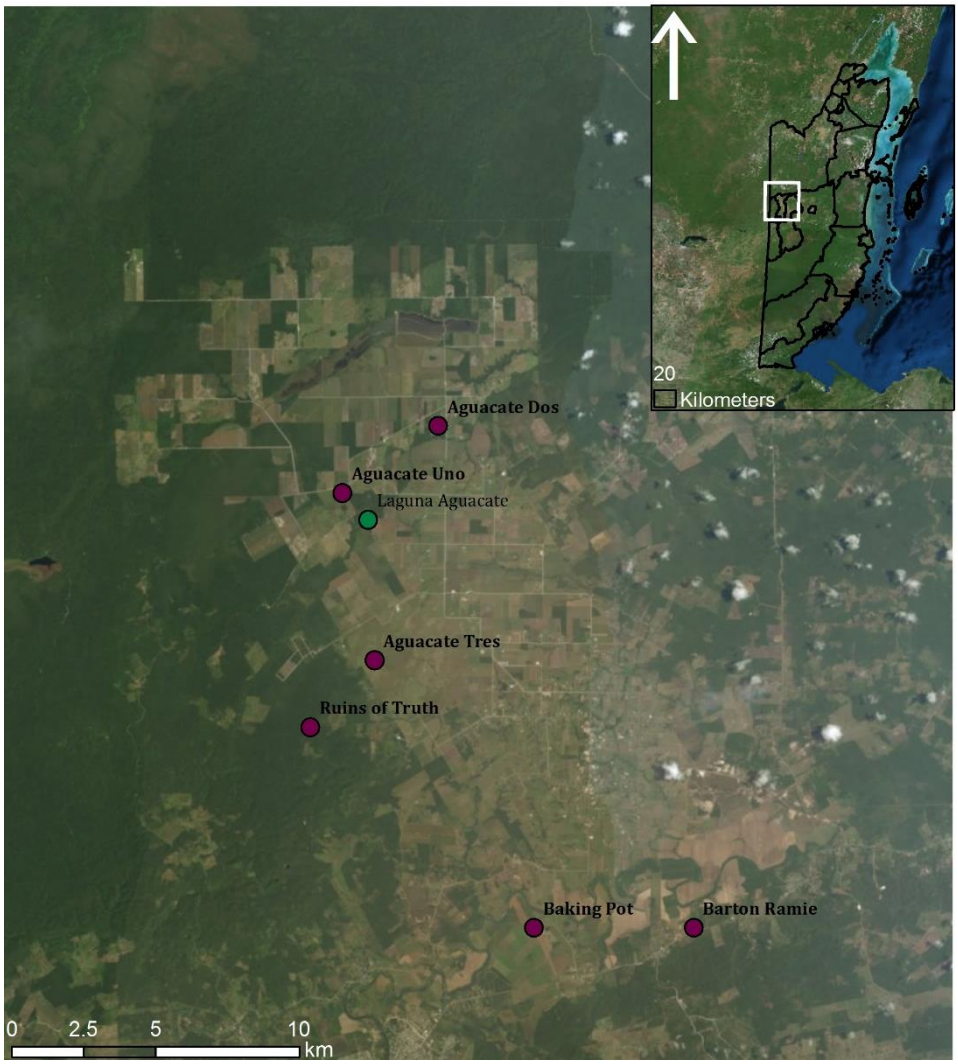
Study site Laguna Aguacate, Belize

Laguna Aguacate is a 0.15km lake located in the Spanish Outlook region of San Ignacio, Belize. The lake itself is surrounded by broadleaf forest along the banks with agricultural activity seen throughout the area. Communication with the locals who live in the area suggests the lake was once used as a recreational lake but activity on it has diminished. The location for coring was decided based on local guides information on the lake. Archaeological context for the area is heavily focused on investigations that occurred in the Belize river valley (Appendix Figure B-1). The largest settlement in the Belize river valley is the site of El Pilar, located >50km. Other sites including smaller Baking Pot (~15km) and Aguacate Uno (~5km north) are smaller density settlements, with Baking Pot thought to have been occupied during the Middle Preclassic (700-400 BCE) (Hoggarth *et al.*, 2014).

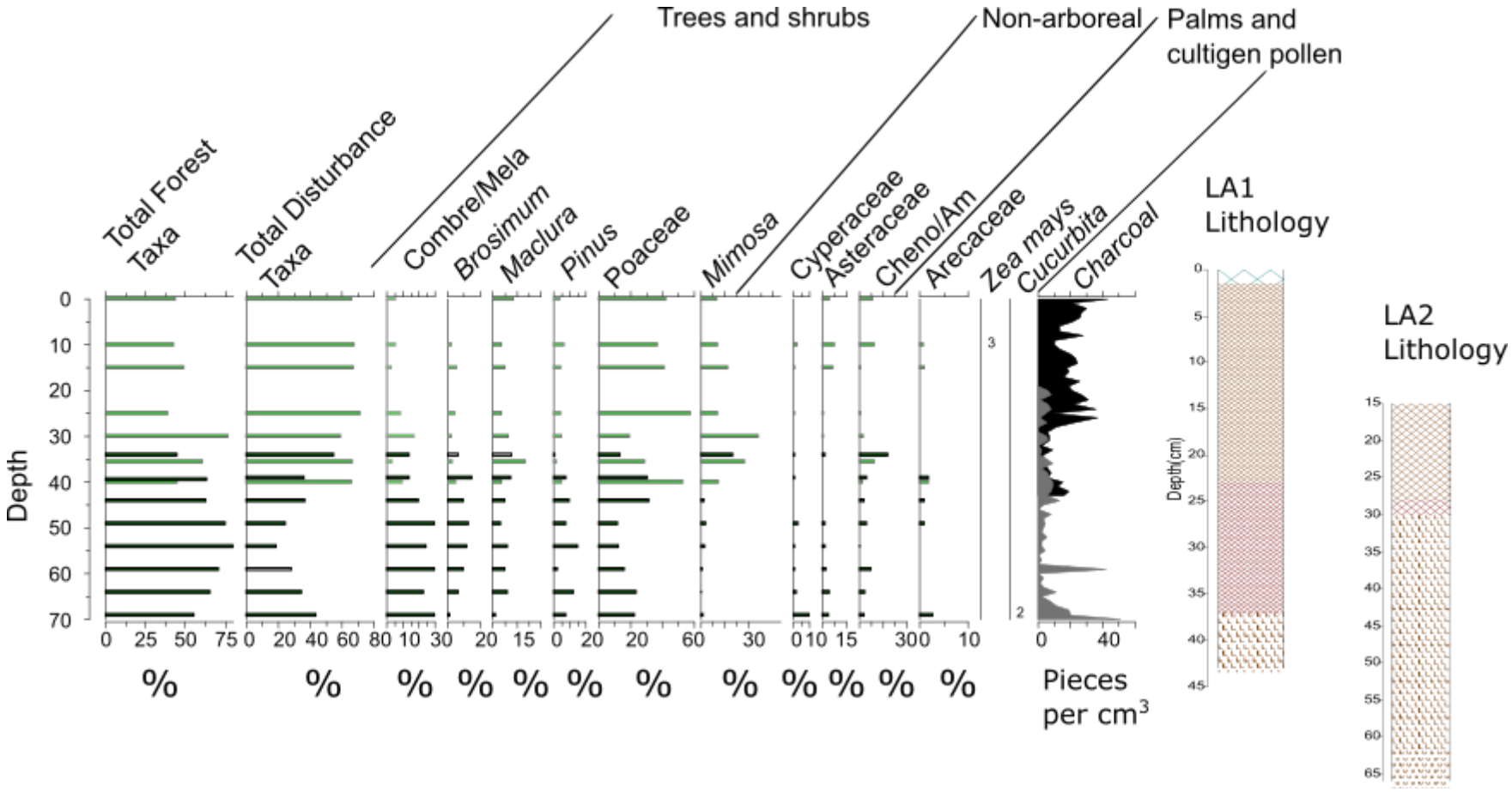
Methods and Preliminary Results

Based on a previous methodology employed from a palaeoecological record from Lamanai (Rushton, 2014), a short-core was extracted from Laguna Aguacate. Based off this previous record, it was assumed that the core would cover the ancient Maya period. Using this surface coring methodology, 70cm’s of lake sediment were extracted. The core was sub-sampled at 0.5cm resolution in the field. To calculate offset associated with the hard-water effect, a paired bulk sediment and macrofossil radiocarbon dating was chosen. The bulk sediment analysis originally showed that the full core covered 585 yrs cal. BP, but the paired macrofossil sample later revealed it only covered the past 210 yrs cal. BP(Appendix Table B-1). The Laguna Aguacate core shows evidence for both squash (*Cucurbita*) and

maize (*Zea mays*) cultivation. Changes in arboreal pollen and increasing charcoal count mainly reflect Mennonite management of the landscape (Appendix Figure B-2).



Appendix Figure B.1 Map of the Laguna Aguacate lake located on the mainland of Belize. Known archaeological sites are also identified.



Appendix Figure B.2 Preliminary pollen and charcoal results from the Laguna Aguacate core. Combre/Mela = Combretaceae/Melastomataceae, Cheno/Am = Chenopodiaceae/Amarantaceae. Dark colours represent the abundances from the overlap core. Sediment log also displayed to show the degree of overlap

Appendix Table B.1 Radiocarbon ages obtained from the Laguna Aguacate core. Core names refer to the primary core (LA1) and the overlap core (LA2)

Code	Material	Age (cal. BP)	Error	Core	Depth (cm)
GdA-5489	Macrofossil	150	35	LA1	34.5
SUERC-81799	Bulk sediment	557	35	LA1	41-42
UCIAMS-210612	Macrofossil	90	25	LA2	33
SUERC-81800	Bulk sediment	327	35	LA2	33-33.5
UCIAMS-210614	Bulk sediment	470	25	LA2	54
SUERC-81801	Bulk sediment	585	35	LA2	63-63.5
UCIAMS-210613	Macrofossil	210	25	LA2	63.5-63.4

Discussion and implications

Whilst the Laguna Aguacate record was not included in the primary thesis, the preliminary results represent important findings regarding land-use in Belize. Firstly, according to radiocarbon dating, the short core from Laguna Aguacate covers approximately ~210 years (Appendix Table B.1). This indicates that the source of the *Cucurbita* cultivation at the base of the core was not from the ancient Maya, but the communities who occupied the region following the Spanish conquest in the 16th century. Potentially this source was practised by modern Mayans, whose land-use practices incorporated the use of squash as a

form of subsistence. With little written accounts available regarding who managed the landscape between the 15th and 20th centuries, the palaeoecological record can provide important information regarding landscape management, showing the landscape was cultivated for a period of time following Spanish contact.

The Mennonite community of Spanish Lookout, who currently own Laguna Aguacate, first occupied the area in 1958. According to primary sourced documents, the first Mennonite inhabitants struck a deal with the Belizean prime minister to produce food for "local consumption and exports"(Loewen, no date). Based on the chronology of the Aguacate core, the record likely captures the occupation of Spanish Lookout by the Mennonite community, along with some degree of land-use (maize cultivation). As the modern landscape of Spanish Lookout has been modified to practice maize cultivation, it represents an analogue to understand the intensity of land-use practices associated with the ancient Maya. With a higher resolution of pollen counting completed throughout this core, it would represent how the landscape was managed by communities between 1700 CE-present. Then, based on this data, if a deeper core was obtained from Laguna Aguacate, patterns of ancient Maya land-use could be compared to this modern record.

Along with representing a modern analogue for land-use, the dating of the Laguna Aguacate core represents an important finding for palaeoecological records in Belize. As mentioned, the coring methodology replicated a well-established core extracted from Lamanai (Rushton, Metcalfe and Whitney, 2012). This core from Lamanai did not use paired dating's for the chronology and instead constructed the age model based on bulk-sediment dating. As the Lamanai record and the Laguna Aguacate record showed similar sedimentological logs, particularly the red-clay layer, it potentially indicates that this Lamanai record covers a similar period as the record presented here. This would have important implications regarding the understanding of ancient Maya land-use as the Lamanai record has been interpreted to show ancient Maya palm management. If the chronologies are deemed to be similar, then this would indicate that the evidence for *Zea mays* and palm cultivation are from the modern period.

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